Jet Shapes of Isolated Photon-Tagged Jets in Pb-Pb and pp Collisions at $\sqrt{s}NN = 5.02$ TeV

CMS Collaboration ; Canelli, Maria Florencia ; Kilminster, Benjamin ; Aarrestad, Thea K ; Brzhechko, Danyyl ; Caminada, Lea ; de Cosa, Annapaoloa ; Del Burgo, Riccardo ; Donato, Silvio ; Galloni, Camilla ; Hreus, Tomas ; Leontsinis, Stefanos ; Mikuni, Vinicius M ; Neutelings, Izaak ; Rauco, Giorgia ; Robmann, Peter ; Salerno, Daniel ; Schweiger, Korbinian ; Seitz, Claudia ; Takahashi, Yuta ; Wertz, Sebastien ; Zucchetta, Alberto ; et al

DOI: https://doi.org/10.1103/PhysRevLett.122.152001

Jet Shapes of Isolated Photon-Tagged Jets in Pb-Pb and pp Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

A. M. Sirunyan *et al.*[*]
(CMS Collaboration)

(Received 23 September 2018; published 17 April 2019)

The modification of jet shapes in Pb-Pb collisions, relative to those in pp collisions, is studied for jets associated with an isolated photon. The data were collected with the CMS detector at the LHC at a nucleon-nucleon center-of-mass energy of 5.02 TeV. Jet shapes are constructed from charged particles with track transverse momenta (p_T) above 1 GeV/c in annuli around the axes of jets with $p_T^{\text{jet}} > 30$ GeV/c associated with an isolated photon with $p_T^{\gamma} > 60$ GeV/c. The jet shape distributions are consistent between peripheral Pb-Pb and pp collisions, but are modified for more central Pb-Pb collisions. In these central Pb-Pb events, a larger fraction of the jet momentum is observed at larger distances from the jet axis compared to pp, reflecting the interaction between the partonic medium created in heavy ion collisions and the traversing partons.

DOI: 10.1103/PhysRevLett.122.152001

The quark-gluon plasma (QGP) [1], a deconfined state of quarks and gluons, can be created in relativistic heavy ion collisions. It can be probed with energetic partons emerging from initial hard scattering processes in the same collisions. The outgoing partons eventually fragment, and each forms a jet of collimated particles that can be observed experimentally. The interactions of the partons with the medium, and therefore the modification of the resulting jets, can be related to the thermodynamical and transport properties of the traversed medium [2–7]. To better understand the dynamics of the QGP, it is important to explore the mechanisms by which the partons lose energy to the medium, whether by radiation, scattering off its pointlike constituents, or by some other processes [8–12].

The CERN LHC Collaborations have studied the medium-induced modifications of jets by measuring the jet yield for a given transverse momentum (p_T) [13–17] and jet substructure [18–29]. In these types of jet measurements, there is limited information on the initial energy of the parton, i.e., before its interaction with the medium. On the other hand, by studying jets produced in association with an electroweak boson, such as a photon or a Z boson, whose p_T can be precisely measured, the initial parent parton p_T can be tightly constrained, as electroweak bosons do not interact strongly with the medium [30–32]. At LHC energies, these types of processes have an additional advantage: jets associated with an electroweak boson are dominated by quark jets for $p_T^{\text{jet}} > 30$ GeV/c [33], hence providing information specifically on quark energy loss, and therefore constraining the dependence of energy loss on parton (quark or gluon) flavor [34,35].

The CMS Collaboration has previously measured the azimuthal correlation and momentum imbalance of isolated photon + jet pairs in proton-proton (pp) and lead-lead (Pb-Pb) collisions at nucleon-nucleon center-of-mass energies of $\sqrt{s_{NN}} = 2.76$ and 5.02 TeV [36,37], and of Z + jet pairs at 5.02 TeV [38]. More recently, the fragmentation functions of jets tagged with a measured the azimuthal correlation measured the azimuthal correlation [39]. A photon is considered isolated if the total transverse energy of other particles in a cone of fixed radius around its direction is small after taking into account the underlying event (UE) contributions as explained in Refs. [37,40]. This definition suppresses dijet events in which a high-p_T photon originates from one of the jets, either via collinear fragmentation of a parton ("fragmentation photons") or via decays of neutral mesons ("decay photons"). The results showed that in central Pb-Pb collisions there is an excess of low-p_T particles and a depletion of high-p_T particles inside the jet cone. The jet fragmentation functions reflect the momentum distribution inside the parton shower in the longitudinal direction, making it highly sensitive to the hadronization process [34]. A complementary observable for medium-induced modifications that features reduced sensitivity to hadronization is the jet radial momentum density profile, i.e., the jet shape, which is a measure of the component of the momentum transverse to the jet axis [41,42]. Jet shape measurements so far were done using inclusive jet [19,28] or dijet samples [23].

This Letter reports the first measurement of the differential jet shape for jets associated with an isolated photon. The differential jet shape $\rho(r)$ is defined as

[*]Full author list given at the end of the Letter.

$$\rho(r) = \frac{1}{\delta r} \frac{\sum_{\text{jets}} \sum_{r_a < r < r_b} (p_T{}^{\text{trk}} / p_T{}^{\text{jet}})}{\sum_{\text{jets}} \sum_{0 < r < r_f} (p_T{}^{\text{trk}} / p_T{}^{\text{jet}})}, \qquad (1)$$

where $\delta r = r_b - r_a$ is the width of the annulus of inner and outer radii r_a and r_b with respect to the jet axis, respectively, p_T^{trk} is the p_T of tracks falling within each annulus of the jet with p_T^{jet}, and $r = \sqrt{(\eta^{\text{jet}} - \eta^{\text{trk}})^2 + (\phi^{\text{jet}} - \phi^{\text{trk}})^2}$ is the distance between the track and the jet axis in pseudorapidity (η) and azimuthal angle (ϕ) plane. The distribution is normalized such that the integral inside the range $0 < r < r_f$ is unity where $r_f = 0.3$. Hence, $\rho(r)$ gives a measure of how the p_T of a jet is distributed (over charged particles) in a direction transverse to the jet axis. The analysis uses Pb-Pb and pp data at $\sqrt{s_{NN}} = 5.02$ TeV collected in 2015, corresponding to integrated luminosities of 404 μb^{-1} and 27.4 pb^{-1}, respectively.

The central feature of the CMS detector is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two end cap sections. Hadron forward (HF) calorimeters extend the coverage up to $|\eta| = 5.2$ and are used for event selection. In addition, in the case of Pb-Pb events, the HF signals are used to determine the degree of overlap ("centrality") of the two colliding Pb nuclei [43] and the event-by-event ϕ angle of maximum particle density ("event plane") [44]. A more detailed description of the CMS detector can be found in Ref. [45].

The event samples are selected online with a trigger requiring a photon with $p_T^\gamma > 40$ GeV/c [37,39]. Additional requirements are applied off-line to remove noncollision events such as beam-gas interactions [46]. For jets and photons, the reconstruction algorithms, analysis selections, and corrections for the energy scale and resolution are the same as in Refs. [37,39]. For Pb-Pb collisions, the event centrality is defined as the fraction of the total inelastic hadronic cross section of these collisions at $\sqrt{s_{NN}} = 5.02$ TeV, starting at 0% for the most central collisions, and is evaluated as percentiles of the distribution of the energy deposited in the HF calorimeters [43]. Results are presented in four centrality intervals: 0%–10%, 10%–30%, 30%–50%, and 50%–100%.

The photon candidates are restricted to the barrel of the ECAL, $|\eta^\gamma| < 1.44$, and are required to have $p_T^\gamma > 60$ GeV/c. The trigger is fully efficient for these requirements. Electron contamination and anomalous signals caused by the interaction of highly ionizing particles with the photodiodes used for the ECAL readout are removed, as described in Ref. [47]. Background from hadronic showers is rejected by requiring that the ratio of the HCAL over ECAL energy inside a cone of radius $\delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.15$ around the photon candidate is smaller than 0.1 [40,47]. Background contributions from fragmentation and decay photons are rejected by imposing the same isolation requirements as in Refs. [37,47]: the p_T sum in a cone of radius 0.4 with respect to the centroid of the cluster, not including the p_T of the cluster and after correcting for the UE (only in Pb-Pb collisions), is required to be less than 1 GeV/c. The dominant remaining background is from ECAL showers initiated by isolated neutral mesons, e.g., π^0, η, and ω, decaying into pairs of photons that, because of their small opening angle, are reconstructed as a single photon. Their contribution can be reduced by a factor of ~2 using an upper limit on the shower shape variable $\sigma_{\eta\eta}$, which is a measure of the width of the ECAL energy cluster distribution in η direction [37,47].

The energy of the reconstructed photons is corrected to account for the losses due to material in front of the ECAL and for incomplete shower containment [48]. An additional correction is applied in Pb-Pb collisions to account for the contribution of the UE formed by soft processes. The corrections are obtained from photon events simulated using the CUETP8M1 tune [49] of the PYTHIA 8.212 [50] Monte Carlo (MC) event generator. The effect of the Pb-Pb UE is modeled by embedding the PYTHIA output in events generated using HYDJET 1.9 [51], which is tuned to reproduce global event properties, such as the UE p_T density, charged-hadron multiplicity and p_T distribution. The size of the resulting energy correction for isolated photons varies from 0% to 10%, depending on the p_T^γ and the centrality. The CMS detector response for generated events is simulated using GEANT4 [52].

Jets are reconstructed from the output of the CMS particle-flow algorithm [53], which aims to reconstruct and identify each individual particle in an event, with an optimized combination of information from the various elements of the detector. The anti-k_T algorithm [54,55] is used to cluster the resulting particles using a distance parameter $R = 0.3$ chosen to minimize the effects of UE fluctuations. In order to subtract the UE background in Pb-Pb collisions, an iterative algorithm [56] is employed [36,43,57]. In pp collisions, where the UE level is negligible, jets are reconstructed without UE subtraction. Additional Pb-Pb (pp) collisions in the same or adjacent bunch crossings are negligible (small) and their effects are found, using MC studies, to be negligible. The jet energy corrections are derived from simulation, separately for pp and Pb-Pb collisions. They are validated via energy balance methods applied to dijet and photon + jet events in pp data [58], reconstructed alternatively with the pp and Pb-Pb reconstruction algorithms. Jets with $|\eta^{\text{jet}}| < 1.6$ and corrected $p_T^{\text{jet}} > 30$ GeV/c are selected.

In each event, photon + jet pairs are formed by associating the highest $p_T{}^\gamma$ isolated photon candidate with all jets that pass the jet selection criteria. An azimuthal separation of $\Delta\phi_{\text{j}\gamma} = |\phi^{\text{jet}} - \phi^\gamma| > 7\pi/8$ is applied to the photon + jet pairs to suppress contributions from background jets

(jets not originating from the same hard scattering as the photon) and from photon + multijet events (the hard scattering produces more than one parton balancing the photon). The tracks used in this measurement have $p_T^{\mathrm{trk}} > 1$ GeV/c, $|\eta^{\mathrm{trk}}| < 2.4$, and must fall within a cone of radius $\delta R = 0.3$ around the jet direction. These selection criteria, as well as the corrections for tracking efficiency, detector acceptance, and misreconstruction rate, are the same as in Ref. [46] for both pp and Pb-Pb data.

To isolate the contribution of photons, jets, and charged particles that are produced in the same hard scattering in Pb-Pb collisions, several sources of combinatorial backgrounds are subtracted: tracks from the UE that fall within the cone around the selected jet, misidentified jets resulting from UE fluctuations, and jets not produced in the same hard parton-parton scatterings as the photon. The shape and magnitude of these contributions to the $\rho(r)$ distributions are estimated from data with an event mixing procedure, in which either the isolated photon or the jet are combined with jets and tracks found in events chosen randomly from a minimum bias (MB) Pb-Pb dataset with similar event characteristics (centrality, interaction vertex position, and event plane angle, which is correlated to particle density in the ϕ direction). The background contribution from UE tracks is estimated by constructing the distribution for each selected jet using tracks from MB events. The backgrounds from jets produced by UE fluctuations or a different hard parton-parton scattering are estimated as in Refs. [36,37]. The normalizations of these combinatorial background distributions are given by the number of MB events used. Simulation shows that the UE particle density can be different between a hard scattering event (PYTHIA+HYDJET) and a MB event (HYDJET only) that have the same reconstructed centrality. Therefore, the normalized background distributions are further scaled with a residual factor to account for this effect before being subtracted from those in photon + jet events.

An additional correction is applied for effects such as detector resolution, particle reconstruction, and UE particles uncorrelated to the true jet. This correction is calculated from the PYTHIA+HYDJET (PYTHIA) sample for the Pb-Pb (pp) results. The distributions from reconstructed (detector-level) jets are corrected to the ones from true (generator-level) jets as a function of r. The correction is calculated in three steps. (i) The jet shapes for reconstructed jets using reconstructed tracks are corrected to the ones that use true charged particles. This step accounts for the reconstructed track yield that decreases with the distance between the track and jet axis, an effect resulting from the correlation between track reconstruction efficiency and jet reconstruction. The average corrections for $r < 0.2(r > 0.2)$ are ~4(5)% for pp and ~4(10)% for 0%–10% centrality Pb-Pb results. (ii) The jet shapes obtained after the first step are corrected to the ones that use true charged particles from the signal PYTHIA event. This step accounts for the correlations between the reconstructed jet and tracks from the UE and is applied for Pb-Pb data only. The average corrections for $r < 0.2(r > 0.2)$ are ~10(15)% for 0%–10% centrality Pb-Pb results. (iii) The jet shapes obtained after the second step are corrected to the ones for true jets. This last step accounts for the difference between the jet shapes for reconstructed and true jets. The average corrections for $r < 0.2(r > 0.2)$ are ~2(3)% for pp and ~20(35)% for 0%–10% centrality Pb-Pb results. The corrections are calculated in bins of r, p_T^{jet}, η^{jet}, p_T^{trk}, and centrality. The largest corrections happen at $r \approx 0.3$ and their average values in the first, second, and third steps for 0%–10% centrality Pb-Pb (pp) collisions are 15 (6)%, 20 (0)%, and 45 (4)%, respectively. Studies have been done separately for the shapes of quark and gluon jets in order to check if the corrections, which do not take parton flavor into account, cause a bias in the results. The corrections improve the agreement between reconstructed and true jets for both quark and gluon jets in both PYTHIA and PYTHIA+HYDJET samples.

A final correction accounts for the photon purity, defined to be the fraction of photons within the set of isolated photon candidates that do not originate from hadron decays and that pass the $\sigma_{\eta\eta}$ requirement. This fraction is extracted from the data using a template fit to the $\sigma_{\eta\eta}$ distribution [36,37]. The shape of the $\rho(r)$ distributions from decay photons is estimated by repeating the analysis selecting photons with larger $\sigma_{\eta\eta}$ (wider shower shapes). The purity values (e.g., 0.68 and 0.82 for 0%–10% and 50%–100% Pb-Pb collisions, respectively) from the shower shape fits are used to adjust the magnitude of this background contribution.

Several sources of systematic uncertainty are considered, including the photon purity, photon isolation, photon energy scale, electron contamination, photon selection efficiency, jet energy scale, jet energy resolution, tracking efficiency, r-dependent corrections, and background subtraction. The total uncertainty in each bin is the sum in quadrature of the individual uncertainties. The quoted systematic uncertainties are an average over all r bins. In the case of the Pb-Pb results, uncertainties are reported only for the 0%–10% centrality interval, which has generally the highest uncertainties among all the centrality bins.

To evaluate the systematic uncertainties related to the isolated photons, the same procedures are applied as in Ref. [37]. The uncertainty in the photon purity is evaluated by varying the components of the shower shape template, as in Ref. [36]. The maximum variations with respect to the nominal case are propagated as systematic uncertainties, amounting to 0.6 (0.3)% for the Pb-Pb (pp) results. In the following, the uncertainties will continue to be quoted for central Pb-Pb events first, then for pp data. The systematic uncertainties resulting from the experimental isolation criteria for a photon are 1.9% and 0.1%. The residual data-to-simulation photon energy scale difference after applying the photon energy corrections is also quoted as a systematic uncertainty of 0.7% for Pb-Pb data, while it is negligible for pp data. The level of electron contamination in the samples before applying the electron rejection criteria is 14% and reduces to roughly 5% after the rejection procedure. An uncertainty is evaluated by repeating the analysis without applying the electron rejection criteria, and scaling down the difference in the $\rho(r)$ distribution to the remaining electron contamination after applying the electron rejection, giving 0.3% and < 0.1%. The efficiency in selecting photons has been extracted from simulation as a function of photon p_T and data are corrected for this efficiency. An uncertainty is assigned by comparing the results to the ones obtained with a correction derived by loosening the selection criteria, given 0.2% and <0.1%.

The uncertainties related to the jet energy resolution and jet energy scale are evaluated as in Ref. [37]. When propagated, the uncertainty related to the jet energy scale amounts to 6.9% and 0.8%, while the energy resolution gives uncertainties of 1.9% and 0.3%. The uncertainty related to the tracking inefficiency is estimated as the difference in the track reconstruction efficiency between data and simulation, as in Ref. [46]. Tracking corrections are varied in a p_T^{trk}-dependent way, giving systematic uncertainties of 1.0% and 0.9%.

Further systematic uncertainties are assigned for the r-dependent correction procedure. First, it is observed in MC simulations that the first step of corrections has a remaining disagreement of 2% at $r \approx 0.3$ between reconstructed tracks and true charged particles, in both the pp and Pb-Pb cases. Second, the model dependence of the corrections is studied by obtaining the quark and gluon jet shape distributions from MC simulations and fitting them to distributions in data. The extracted templates are varied by the fit uncertainty. The difference between the nominal and varied templates is quoted as systematic uncertainty, amounting to 0.5 (1)% and 3 (4)% in the $r < 0.2 (r > 0.2)$ case, for pp and Pb-Pb results, respectively.

For Pb-Pb collisions a systematic uncertainty for the background subtraction is estimated by combining two independent sources. First, results are obtained using an alternative background subtraction procedure (the so-called η-reflection method [20]) and compared to the nominal method. Second, nominal results are compared to the ones where the background distributions are not scaled for the UE particle density difference seen in simulation. The combined difference of 3.5% is assigned as the uncertainty.

The upper panel of Fig. 1 shows the differential jet shape $\rho(r)$ for both Pb-Pb and pp collisions, and PYTHIA simulation. The ratio of Pb-Pb to pp (simulated to pp) data distributions are shown in the lower panel. The simulation is slightly higher than the pp data at large r, but describes the pp data to within 10% in each bin, allowing its use to derive the r-dependent corrections. The uncertainties considered correlated between the pp and Pb-Pb datasets (from photon isolation, photon purity, photon efficiency, electron rejection, jet energy scale, jet energy resolution, tracking efficiency, and from the r-dependent procedure corrections) partially cancel in the ratio. The distribution in 50%–100% Pb-Pb collisions is consistent with that in pp collisions. The difference between the pp and the 0%–10% (0%–30%) Pb-Pb results was quantified by comparing the two distributions with a χ^2 test, including all statistical and systematical uncertainties. The p value found was 0.029 (0.017). This shows that, with a p-value cutoff of 0.05, the two sets of results are incompatible with each other for the two most central Pb-Pb collisions bins.

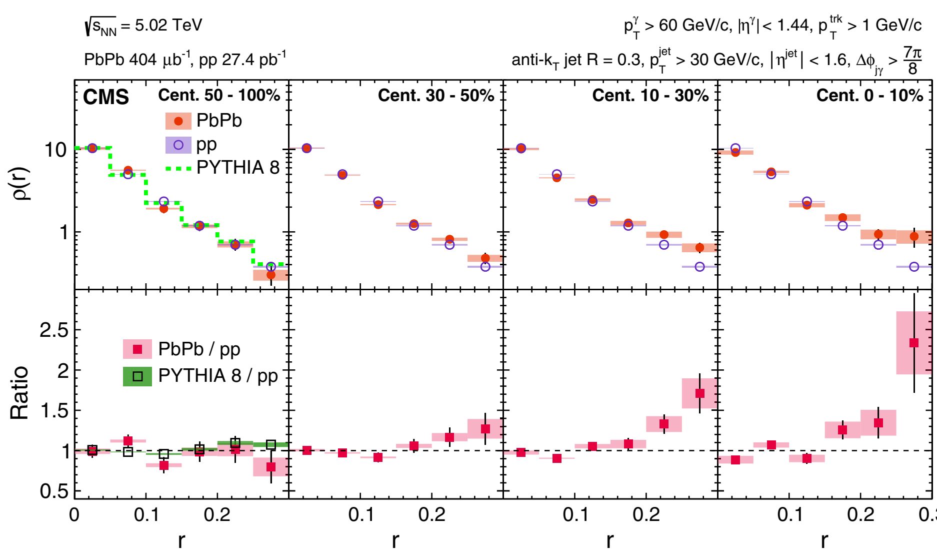

FIG. 1. Upper: The differential jet shape $\rho(r)$ for jets associated with an isolated photon for (from left to right) 50%–100%, 30%–50%, 10%–30%, 0%–10% Pb-Pb (solid circles), pp (open circles) collisions, and from PYTHIA simulation (histogram). Lower: The ratios of the Pb-Pb and pp distributions. For the pp results, the ratio is to the PYTHIA distribution. The vertical lines through the points represent statistical uncertainties, while the shaded colored boxes indicate the total systematic uncertainties in data.

In these central collisions, an enhancement of the $\rho(r)$ distribution with respect to the reference pp data is observed at $r \approx 0.3$. When integrated over different r intervals, the results show that ~5% of pp jet energy is beyond $r > 0.2$. For jets in 0%–10% Pb-Pb collisions the jet energy fraction changes to ~9%. This implies that in Pb-Pb data a larger fraction of the jet momentum is carried at large distances from the jet axis. The enhancement seen at large r is in qualitative agreement with the inclusive jet shape results in Refs. [19,28], and both the leading and subleading jet shapes in Ref. [23]. In contrast, no significant depletion is seen in central collisions for intermediate r, as was observed in the aforementioned inclusive jet shape and leading jet shape results. This could be because of tagging the jet sample with isolated photons, which increases the quark jet fraction, and because of the lower p_T^{jet} threshold, which increases the fraction of less collimated jets (including those with a larger relative energy loss). On the other hand, the $\rho(r)$ distributions decrease rapidly with r, with the bulk of the jet energy being concentrated at small r in both collision systems. Since the fraction of $\rho(r)$ shifted from small to large r because of medium modifications in Pb-Pb collisions is small compared to the integrated fraction at small r, the depletion cannot appear large.

In summary, the differential jet shapes for jets associated with isolated photons are measured in pp and Pb-Pb collisions for the first time. They are constructed using charged particles with transverse momentum $p_T^{\text{trk}} > 1\ \text{GeV}/c$, for jets with $p_T^{\text{jet}} > 30\ \text{GeV}/c$, which are associated with an isolated photon with $p_T^{\gamma} > 60\ \text{GeV}/c$. While the distribution from the most peripheral (50%–100%) Pb-Pb collisions is consistent with that in pp data, a modification of the jet shape in Pb-Pb collisions is observed in more central events. The 0%–10% (0%–30%) Pb-Pb $\rho(r)$ is enhanced for the distance between the track and the jet axis $r \gtrsim 0.15$ (0.20). No significant suppression is seen at intermediate r. The modifications demonstrate that for hard scatterings that predominantly produce quarks with similar momentum distributions in pp and Pb-Pb collisions, as identified by the photon tag, the jet momentum is distributed at greater radial distance in Pb-Pb collisions. This significant redistribution of energy observed in central Pb-Pb collisions, compared with pp and peripheral Pb-Pb collisions, can be interpreted as a direct observation of jet broadening in the quark-gluon plasma (QGP). This first measurement of radial momentum density profile for jets tagged by an isolated photon, which constrains the information about the jet energy before any loss occurred while traversing the QGP, constitutes a new unambiguous reference for testing theoretical models of parton-medium interactions.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

[1] F. Karsch, The phase transition to the quark gluon plasma: recent results from lattice calculations, Nucl. Phys. **A590**, 367 (1995).

[2] D. A. Appel, Jets as a probe of quark-gluon plasmas, Phys. Rev. D **33**, 717 (1986).

[3] J. P. Blaizot and L. D. McLerran, Jets in expanding quark-gluon plasmas, Phys. Rev. D **34**, 2739 (1986).

[4] M. Gyulassy and M. Plümer, Jet quenching in dense matter, Phys. Lett. B **243**, 432 (1990).

[5] X.-N. Wang and M. Gyulassy, Gluon Shadowing and Jet Quenching in $A + A$ Collisions at $\sqrt{s} = 200A$ GeV, Phys. Rev. Lett. **68**, 1480 (1992).

[6] R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigne, and D. Schiff, Radiative energy loss and $p_{\perp}$-broadening of high energy partons in nuclei, Nucl. Phys. **B484**, 265 (1997).

[7] B. G. Zakharov, Radiative energy loss of high-energy quarks in finite-size nuclear matter and quark-gluon plasma, JETP Lett. **65**, 615 (1997).

[8] M. Gyulassy, P. Levai, and I. Vitev, Reaction operator approach to nonAbelian energy loss, Nucl. Phys. **B594**, 371 (2001).

[9] M. Djordjevic and M. Gyulassy, Heavy quark radiative energy loss in QCD matter, Nucl. Phys. **A733**, 265 (2004).

[10] G. Ovanesyan and I. Vitev, An effective theory for jet propagation in dense QCD matter: Jet broadening and

medium-induced bremsstrahlung, J. High Energy Phys. 06 (2011) 080.
[11] X.-N. Wang and X. Guo, Multiple parton scattering in nuclei: Parton energy loss, Nucl. Phys. **A696**, 788 (2001).
[12] K. M. Burke, A. Buzzatti, N. Chang, C. Gale, M. Gyulassy, U. Heinz, S. Jeon, A. Majumder, B. Müller, G.-Y. Qin, B. Schenke, C. Shen, X.-N. Wang, J. Xu, C. Young, and H. Zhang (JET Collaboration), Extracting the jet transport coefficient from jet quenching in high-energy heavy-ion collisions, Phys. Rev. C **90**, 014909 (2014).
[13] ATLAS Collaboration, Measurement of the jet radius and transverse momentum dependence of inclusive jet suppression in lead-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV with the ATLAS detector, Phys. Lett. B **719**, 220 (2013).
[14] ALICE Collaboration, Measurement of charged jet suppression in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, J. High Energy Phys. 03 (2014) 013.
[15] ATLAS Collaboration, Measurements of the Nuclear Modification Factor for Jets in Pb + Pb Collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV with the ATLAS Detector, Phys. Rev. Lett. **114**, 072302 (2015).
[16] ALICE Collaboration, Measurement of jet suppression in central Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, Phys. Lett. B **746**, 1 (2015).
[17] CMS Collaboration, Measurement of inclusive jet cross sections in pp and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, Phys. Rev. C **96**, 015202 (2017).
[18] CMS Collaboration, Measurement of jet fragmentation into charged particles in pp and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, J. High Energy Phys. 10 (2012) 087.
[19] CMS Collaboration, Modification of jet shapes in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, Phys. Lett. B **730**, 243 (2014).
[20] CMS Collaboration, Measurement of jet fragmentation in PbPb and pp collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, Phys. Rev. C **90**, 024908 (2014).
[21] ATLAS Collaboration, Measurement of inclusive jet charged-particle fragmentation functions in Pb + Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV with the ATLAS detector, Phys. Lett. B **739**, 320 (2014).
[22] CMS Collaboration, Measurement of transverse momentum relative to dijet systems in PbPb and pp collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, J. High Energy Phys. 01 (2016) 006.
[23] CMS Collaboration, Decomposing transverse momentum balance contributions for quenched jets in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, J. High Energy Phys. 11 (2016) 055.
[24] CMS Collaboration, Correlations between jets and charged particles in PbPb and pp collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, J. High Energy Phys. 02 (2016) 156.
[25] ALICE Collaboration, First measurement of jet mass in Pb-Pb and p-Pb collisions at the LHC, Phys. Lett. B **776**, 249 (2018).
[26] CMS Collaboration, Measurement of the Splitting Function in pp and Pb-Pb Collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, Phys. Rev. Lett. **120**, 142302 (2018).
[27] ATLAS Collaboration, Measurement of jet fragmentation in Pb + Pb and pp collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV with the ATLAS detector at the LHC, Eur. Phys. J. C **77**, 379 (2017).
[28] CMS Collaboration, Jet properties in PbPb and pp collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, J. High Energy Phys. 05 (2018) 006.
[29] ALICE Collaboration, Medium modification of the shape of small-radius jets in central Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, J. High Energy Phys. 10 (2018) 139.
[30] X.-N. Wang, Z. Huang, and I. Sarcevic, Jet Quenching in the Opposite Direction of a Tagged Photon in High-Energy Heavy Ion Collisions, Phys. Rev. Lett. **77**, 231 (1996).
[31] X.-N. Wang and Z. Huang, Medium-induced parton energy loss in γ + jet events of high-energy heavy-ion collisions, Phys. Rev. C **55**, 3047 (1997).
[32] W. Dai, I. Vitev, and B.-W. Zhang, Momentum Imbalance of Isolated Photon-Tagged Jet Production at RHIC and LHC, Phys. Rev. Lett. **110**, 142001 (2013).
[33] R. B. Neufeld, I. Vitev, and B. W. Zhang, Physics of Z^0/γ^*-tagged jets at energies available at the CERN large hadron collider, Phys. Rev. C **83**, 034902 (2011).
[34] J. Casalderrey-Solana, D. Can Gulhan, J. Guilherme Milhano, D. Pablos, and K. Rajagopal, Predictions for boson-jet observables and fragmentation function ratios from a hybrid strong/weak coupling model for jet quenching, J. High Energy Phys. 03 (2016) 053.
[35] Z.-B. Kang, I. Vitev, and H. Xing, Vector-boson-tagged jet production in heavy ion collisions at energies available at the CERN large hadron collider, Phys. Rev. C **96**, 014912 (2017).
[36] CMS Collaboration, Studies of jet quenching using isolated-photon + jet correlations in PbPb and pp collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, Phys. Lett. B **718**, 773 (2013).
[37] CMS Collaboration, Study of jet quenching with isolated-photon + jet correlations in PbPb and pp collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, Phys. Lett. B **785**, 14 (2018).
[38] CMS Collaboration, Study of Jet Quenching with Z + jet Correlations in Pb-Pb and pp Collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, Phys. Rev. Lett. **119**, 082301 (2017).
[39] CMS Collaboration, Observation of Medium Induced Modifications of Jet Fragmentation in PbPb Collisions Using Isolated-Photon-Tagged Jets, Phys. Rev. Lett. **121**, 242301 (2018).
[40] CMS Collaboration, Measurement of the Isolated Prompt Photon Production Cross Section in pp Collisions at $\sqrt{s} = 7$ TeV, Phys. Rev. Lett. **106**, 082001 (2011).
[41] I. Vitev, S. Wicks, and B.-W. Zhang, A Theory of jet shapes and cross sections: From hadrons to nuclei, J. High Energy Phys. 11 (2008) 093.
[42] Y.-T. Chien and I. Vitev, Towards the understanding of jet shapes and cross sections in heavy ion collisions using soft-collinear effective theory, J. High Energy Phys. 05 (2016) 023.
[43] CMS Collaboration, Observation and studies of jet quenching in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, Phys. Rev. C **84**, 024906 (2011).
[44] CMS Collaboration, Azimuthal Anisotropy of Charged Particles at High Transverse Momenta in PbPb Collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV, Phys. Rev. Lett. **109**, 022301 (2012).
[45] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. **3**, S08004 (2008).
[46] CMS Collaboration, Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, J. High Energy Phys. 04 (2017) 039.

[47] CMS Collaboration, Measurement of isolated photon production in pp and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Phys. Lett. B **710**, 256 (2012).

[48] CMS Collaboration, Performance of photon reconstruction and identification with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV, J. Instrum. **10**, P08010 (2015).

[49] CMS Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements, Eur. Phys. J. C **76**, 155 (2016).

[50] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, An introduction to PYTHIA 8.2, Comput. Phys. Commun. **191**, 159 (2015).

[51] I. P. Lokhtin and A. M. Snigirev, A model of jet quenching in ultrarelativistic heavy ion collisions and high-p_T hadron spectra at RHIC, Eur. Phys. J. C **45**, 211 (2006).

[52] S. Agostinelli *et al.* (GEANT4 Collaboration), GEANT4—a simulation toolkit, Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).

[53] CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector, J. Instrum. **12**, P10003 (2017).

[54] M. Cacciari, G. P. Salam, and G. Soyez, The anti-k_T jet clustering algorithm, J. High Energy Phys. 04 (2008) 063.

[55] M. Cacciari, G. P. Salam, and G. Soyez, FastJet user manual, Eur. Phys. J. C **72**, 1896 (2012).

[56] O. Kodolova, I. Vardanian, A. Nikitenko, and A. Oulianov, The performance of the jet identification and reconstruction in heavy ions collisions with CMS detector, Eur. Phys. J. C **50**, 117 (2007).

[57] CMS Collaboration, Jet momentum dependence of jet quenching in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Phys. Lett. B **712**, 176 (2012).

[58] CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV, J. Instrum. **12**, P02014 (2017).

A. M. Sirunyan,[1] A. Tumasyan,[1] W. Adam,[2] F. Ambrogi,[2] E. Asilar,[2] T. Bergauer,[2] J. Brandstetter,[2] M. Dragicevic,[2] J. Erö,[2] A. Escalante Del Valle,[2] M. Flechl,[2] R. Frühwirth,[2,b] V. M. Ghete,[2] J. Hrubec,[2] M. Jeitler,[2,b] N. Krammer,[2] I. Krätschmer,[2] D. Liko,[2] T. Madlener,[2] I. Mikulec,[2] N. Rad,[2] H. Rohringer,[2] J. Schieck,[2,b] R. Schöfbeck,[2] M. Spanring,[2] D. Spitzbart,[2] A. Taurok,[2] W. Waltenberger,[2] J. Wittmann,[2] C.-E. Wulz,[2,b] M. Zarucki,[2] V. Chekhovsky,[3] V. Mossolov,[3] J. Suarez Gonzalez,[3] E. A. De Wolf,[4] D. Di Croce,[4] X. Janssen,[4] J. Lauwers,[4] M. Pieters,[4] H. Van Haevermaet,[4] P. Van Mechelen,[4] N. Van Remortel,[4] S. Abu Zeid,[5] F. Blekman,[5] J. D'Hondt,[5] I. De Bruyn,[5] J. De Clercq,[5] K. Deroover,[5] G. Flouris,[5] D. Lontkovskyi,[5] S. Lowette,[5] I. Marchesini,[5] S. Moortgat,[5] L. Moreels,[5] Q. Python,[5] K. Skovpen,[5] S. Tavernier,[5] W. Van Doninck,[5] P. Van Mulders,[5] I. Van Parijs,[5] D. Beghin,[6] B. Bilin,[6] H. Brun,[6] B. Clerbaux,[6] G. De Lentdecker,[6] H. Delannoy,[6] B. Dorney,[6] G. Fasanella,[6] L. Favart,[6] R. Goldouzian,[6] A. Grebenyuk,[6] A. K. Kalsi,[6] T. Lenzi,[6] J. Luetic,[6] N. Postiau,[6] E. Starling,[6] L. Thomas,[6] C. Vander Velde,[6] P. Vanlaer,[6] D. Vannerom,[6] Q. Wang,[6] T. Cornelis,[7] D. Dobur,[7] A. Fagot,[7] M. Gul,[7] I. Khvastunov,[7,c] D. Poyraz,[7] C. Roskas,[7] D. Trocino,[7] M. Tytgat,[7] W. Verbeke,[7] B. Vermassen,[7] M. Vit,[7] N. Zaganidis,[7] H. Bakhshiansohi,[8] O. Bondu,[8] S. Brochet,[8] G. Bruno,[8] C. Caputo,[8] P. David,[8] C. Delaere,[8] M. Delcourt,[8] A. Giammanco,[8] G. Krintiras,[8] V. Lemaitre,[8] A. Magitteri,[8] A. Mertens,[8] M. Musich,[8] K. Piotrzkowski,[8] A. Saggio,[8] M. Vidal Marono,[8] S. Wertz,[8] J. Zobec,[8] F. L. Alves,[9] G. A. Alves,[9] M. Correa Martins Junior,[9] G. Correia Silva,[9] C. Hensel,[9] A. Moraes,[9] M. E. Pol,[9] P. Rebello Teles,[9] E. Belchior Batista Das Chagas,[10] W. Carvalho,[10] J. Chinellato,[10,d] E. Coelho,[10] E. M. Da Costa,[10] G. G. Da Silveira,[10,e] D. De Jesus Damiao,[10] C. De Oliveira Martins,[10] S. Fonseca De Souza,[10] H. Malbouisson,[10] D. Matos Figueiredo,[10] M. Melo De Almeida,[10] C. Mora Herrera,[10] L. Mundim,[10] H. Nogima,[10] W. L. Prado Da Silva,[10] L. J. Sanchez Rosas,[10] A. Santoro,[10] A. Sznajder,[10] M. Thiel,[10] E. J. Tonelli Manganote,[10,d] F. Torres Da Silva De Araujo,[10] A. Vilela Pereira,[10] S. Ahuja,[11a] C. A. Bernardes,[11a] L. Calligaris,[11a] T. R. Fernandez Perez Tomei,[11a] E. M. Gregores,[11a,11b] P. G. Mercadante,[11a,11b] S. F. Novaes,[11a] Sandra S. Padula,[11a] A. Aleksandrov,[12] R. Hadjiiska,[12] P. Iaydjiev,[12] A. Marinov,[12] M. Misheva,[12] M. Rodozov,[12] M. Shopova,[12] G. Sultanov,[12] A. Dimitrov,[13] L. Litov,[13] B. Pavlov,[13] P. Petkov,[13] W. Fang,[14,f] X. Gao,[14,f] L. Yuan,[14] M. Ahmad,[15] J. G. Bian,[15] G. M. Chen,[15] H. S. Chen,[15] M. Chen,[15] Y. Chen,[15] C. H. Jiang,[15] D. Leggat,[15] H. Liao,[15] Z. Liu,[15] F. Romeo,[15] S. M. Shaheen,[15,g] A. Spiezia,[15] J. Tao,[15] Z. Wang,[15] E. Yazgan,[15] H. Zhang,[15] S. Zhang,[15,g] J. Zhao,[15] Y. Ban,[16] G. Chen,[16] A. Levin,[16] J. Li,[16] L. Li,[16] Q. Li,[16] Y. Mao,[16] S. J. Qian,[16] D. Wang,[16] Z. Xu,[16] Y. Wang,[17] C. Avila,[18] A. Cabrera,[18] C. A. Carrillo Montoya,[18] L. F. Chaparro Sierra,[18] C. Florez,[18] C. F. González Hernández,[18] M. A. Segura Delgado,[18] B. Courbon,[19] N. Godinovic,[19] D. Lelas,[19] I. Puljak,[19] T. Sculac,[19] Z. Antunovic,[20] M. Kovac,[20] V. Brigljevic,[21] D. Ferencek,[21] K. Kadija,[21] B. Mesic,[21] A. Starodumov,[21,h] T. Susa,[21] M. W. Ather,[22] A. Attikis,[22] M. Kolosova,[22] G. Mavromanolakis,[22] J. Mousa,[22] C. Nicolaou,[22] F. Ptochos,[22] P. A. Razis,[22] H. Rykaczewski,[22] M. Finger,[23,i] M. Finger Jr.,[23,i] E. Ayala,[24] E. Carrera Jarrin,[25] Y. Assran,[26,j,k] S. Elgammal,[26,j]

S. Khalil,[26,l] S. Bhowmik,[27] A. Carvalho Antunes De Oliveira,[27] R. K. Dewanjee,[27] K. Ehataht,[27] M. Kadastik,[27] M. Raidal,[27] C. Veelken,[27] P. Eerola,[28] H. Kirschenmann,[28] J. Pekkanen,[28] M. Voutilainen,[28] J. Havukainen,[29] J. K. Heikkilä,[29] T. Järvinen,[29] V. Karimäki,[29] R. Kinnunen,[29] T. Lampén,[29] K. Lassila-Perini,[29] S. Laurila,[29] S. Lehti,[29] T. Lindén,[29] P. Luukka,[29] T. Mäenpää,[29] H. Siikonen,[29] E. Tuominen,[29] J. Tuominiemi,[29] T. Tuuva,[30] M. Besancon,[31] F. Couderc,[31] M. Dejardin,[31] D. Denegri,[31] J. L. Faure,[31] F. Ferri,[31] S. Ganjour,[31] A. Givernaud,[31] P. Gras,[31] G. Hamel de Monchenault,[31] P. Jarry,[31] C. Leloup,[31] E. Locci,[31] J. Malcles,[31] G. Negro,[31] J. Rander,[31] A. Rosowsky,[31] M. Ö. Sahin,[31] M. Titov,[31] A. Abdulsalam,[32,m] C. Amendola,[32] I. Antropov,[32] F. Beaudette,[32] P. Busson,[32] C. Charlot,[32] R. Granier de Cassagnac,[32] I. Kucher,[32] A. Lobanov,[32] J. Martin Blanco,[32] C. Martin Perez,[32] M. Nguyen,[32] C. Ochando,[32] G. Ortona,[32] P. Pigard,[32] J. Rembser,[32] R. Salerno,[32] J. B. Sauvan,[32] Y. Sirois,[32] A. G. Stahl Leiton,[32] A. Zabi,[32] A. Zghiche,[32] J.-L. Agram,[33,n] J. Andrea,[33] D. Bloch,[33] J.-M. Brom,[33] E. C. Chabert,[33] V. Cherepanov,[33] C. Collard,[33] E. Conte,[33,n] J.-C. Fontaine,[33,n] D. Gelé,[33] U. Goerlach,[33] M. Jansová,[33] A.-C. Le Bihan,[33] N. Tonon,[33] P. Van Hove,[33] S. Gadrat,[34] S. Beauceron,[35] C. Bernet,[35] G. Boudoul,[35] N. Chanon,[35] R. Chierici,[35] D. Contardo,[35] P. Depasse,[35] H. El Mamouni,[35] J. Fay,[35] L. Finco,[35] S. Gascon,[35] M. Gouzevitch,[35] G. Grenier,[35] B. Ille,[35] F. Lagarde,[35] I. B. Laktineh,[35] H. Lattaud,[35] M. Lethuillier,[35] L. Mirabito,[35] S. Perries,[35] A. Popov,[35,o] V. Sordini,[35] G. Touquet,[35] M. Vander Donckt,[35] S. Viret,[35] T. Toriashvili,[36,p] Z. Tsamalaidze,[37,i] C. Autermann,[38] L. Feld,[38] M. K. Kiesel,[38] K. Klein,[38] M. Lipinski,[38] M. Preuten,[38] M. P. Rauch,[38] C. Schomakers,[38] J. Schulz,[38] M. Teroerde,[38] B. Wittmer,[38] A. Albert,[39] D. Duchardt,[39] M. Erdmann,[39] S. Erdweg,[39] T. Esch,[39] R. Fischer,[39] S. Ghosh,[39] A. Güth,[39] T. Hebbeker,[39] C. Heidemann,[39] K. Hoepfner,[39] H. Keller,[39] L. Mastrolorenzo,[39] M. Merschmeyer,[39] A. Meyer,[39] P. Millet,[39] S. Mukherjee,[39] T. Pook,[39] M. Radziej,[39] H. Reithler,[39] M. Rieger,[39] A. Schmidt,[39] D. Teyssier,[39] S. Thüer,[39] G. Flügge,[40] O. Hlushchenko,[40] T. Kress,[40] A. Künsken,[40] T. Müller,[40] A. Nehrkorn,[40] A. Nowack,[40] C. Pistone,[40] O. Pooth,[40] D. Roy,[40] H. Sert,[40] A. Stahl,[40,q] M. Aldaya Martin,[41] T. Arndt,[41] C. Asawatangtrakuldee,[41] I. Babounikau,[41] K. Beernaert,[41] O. Behnke,[41] U. Behrens,[41] A. Bermúdez Martínez,[41] D. Bertsche,[41] A. A. Bin Anuar,[41] K. Borras,[41,r] V. Botta,[41] A. Campbell,[41] P. Connor,[41] C. Contreras-Campana,[41] V. Danilov,[41] A. De Wit,[41] M. M. Defranchis,[41] C. Diez Pardos,[41] D. Domínguez Damiani,[41] G. Eckerlin,[41] T. Eichhorn,[41] A. Elwood,[41] E. Eren,[41] E. Gallo,[41,s] A. Geiser,[41] A. Grohsjean,[41] M. Guthoff,[41] M. Haranko,[41] A. Harb,[41] J. Hauk,[41] H. Jung,[41] M. Kasemann,[41] J. Keaveney,[41] C. Kleinwort,[41] J. Knolle,[41] D. Krücker,[41] W. Lange,[41] A. Lelek,[41] T. Lenz,[41] J. Leonard,[41] K. Lipka,[41] W. Lohmann,[41,t] R. Mankel,[41] I.-A. Melzer-Pellmann,[41] A. B. Meyer,[41] M. Meyer,[41] M. Missiroli,[41] G. Mittag,[41] J. Mnich,[41] V. Myronenko,[41] S. K. Pflitsch,[41] D. Pitzl,[41] A. Raspereza,[41] M. Savitskyi,[41] P. Saxena,[41] P. Schütze,[41] C. Schwanenberger,[41] R. Shevchenko,[41] A. Singh,[41] H. Tholen,[41] O. Turkot,[41] A. Vagnerini,[41] G. P. Van Onsem,[41] R. Walsh,[41] Y. Wen,[41] K. Wichmann,[41] C. Wissing,[41] O. Zenaiev,[41] R. Aggleton,[42] S. Bein,[42] L. Benato,[42] A. Benecke,[42] V. Blobel,[42] T. Dreyer,[42] A. Ebrahimi,[42] E. Garutti,[42] D. Gonzalez,[42] P. Gunnellini,[42] J. Haller,[42] A. Hinzmann,[42] A. Karavdina,[42] G. Kasieczka,[42] R. Klanner,[42] R. Kogler,[42] N. Kovalchuk,[42] S. Kurz,[42] V. Kutzner,[42] J. Lange,[42] D. Marconi,[42] J. Multhaup,[42] M. Niedziela,[42] C. E. N. Niemeyer,[42] D. Nowatschin,[42] A. Perieanu,[42] A. Reimers,[42] O. Rieger,[42] C. Scharf,[42] P. Schleper,[42] S. Schumann,[42] J. Schwandt,[42] J. Sonneveld,[42] H. Stadie,[42] G. Steinbrück,[42] F. M. Stober,[42] M. Stöver,[42] A. Vanhoefer,[42] B. Vormwald,[42] I. Zoi,[42] M. Akbiyik,[43] C. Barth,[43] M. Baselga,[43] S. Baur,[43] E. Butz,[43] R. Caspart,[43] T. Chwalek,[43] F. Colombo,[43] W. De Boer,[43] A. Dierlamm,[43] K. El Morabit,[43] N. Faltermann,[43] B. Freund,[43] M. Giffels,[43] M. A. Harrendorf,[43] F. Hartmann,[43,q] S. M. Heindl,[43] U. Husemann,[43] F. Kassel,[43,q] I. Katkov,[43,o] S. Kudella,[43] S. Mitra,[43] M. U. Mozer,[43] Th. Müller,[43] M. Plagge,[43] G. Quast,[43] K. Rabbertz,[43] M. Schröder,[43] I. Shvetsov,[43] G. Sieber,[43] H. J. Simonis,[43] R. Ulrich,[43] S. Wayand,[43] M. Weber,[43] T. Weiler,[43] S. Williamson,[43] C. Wöhrmann,[43] R. Wolf,[43] G. Anagnostou,[44] G. Daskalakis,[44] T. Geralis,[44] A. Kyriakis,[44] D. Loukas,[44] G. Paspalaki,[44] I. Topsis-Giotis,[44] G. Karathanasis,[45] S. Kesisoglou,[45] P. Kontaxakis,[45] A. Panagiotou,[45] I. Papavergou,[45] N. Saoulidou,[45] E. Tziaferi,[45] K. Vellidis,[45] K. Kousouris,[46] I. Papakrivopoulos,[46] G. Tsipolitis,[46] I. Evangelou,[47] C. Foudas,[47] P. Gianneios,[47] P. Katsoulis,[47] P. Kokkas,[47] S. Mallios,[47] N. Manthos,[47] I. Papadopoulos,[47] E. Paradas,[47] J. Strologas,[47] F. A. Triantis,[47] D. Tsitsonis,[47] M. Bartók,[48,u] M. Csanad,[48] N. Filipovic,[48] P. Major,[48] M. I. Nagy,[48] G. Pasztor,[48] O. Surányi,[48] G. I. Veres,[48] G. Bencze,[49] C. Hajdu,[49] D. Horvath,[49,v] Á. Hunyadi,[49] F. Sikler,[49] T. Á. Vámi,[49] V. Veszpremi,[49] G. Vesztergombi,[49,a,u] N. Beni,[50] S. Czellar,[50] J. Karancsi,[50,w] A. Makovec,[50] J. Molnar,[50] Z. Szillasi,[50] P. Raics,[51] Z. L. Trocsanyi,[51] B. Ujvari,[51] S. Choudhury,[52] J. R. Komaragiri,[52] P. C. Tiwari,[52] S. Bahinipati,[53,x] C. Kar,[53] P. Mal,[53] K. Mandal,[53] A. Nayak,[53,y] D. K. Sahoo,[53,x] S. K. Swain,[53] S. Bansal,[54] S. B. Beri,[54] V. Bhatnagar,[54] S. Chauhan,[54] R. Chawla,[54] N. Dhingra,[54] R. Gupta,[54] A. Kaur,[54] M. Kaur,[54] S. Kaur,[54] R. Kumar,[54] P. Kumari,[54] M. Lohan,[54] A. Mehta,[54] K. Sandeep,[54] S. Sharma,[54] J. B. Singh,[54] A. K. Virdi,[54] G. Walia,[54] A. Bhardwaj,[55] B. C. Choudhary,[55] R. B. Garg,[55]

M. Gola,[55] S. Keshri,[55] Ashok Kumar,[55] S. Malhotra,[55] M. Naimuddin,[55] P. Priyanka,[55] K. Ranjan,[55] Aashaq Shah,[55] R. Sharma,[55] R. Bhardwaj,[56,z] M. Bharti,[56,z] R. Bhattacharya,[56] S. Bhattacharya,[56] U. Bhawandeep,[56,z] D. Bhowmik,[56] S. Dey,[56] S. Dutt,[56,z] S. Dutta,[56] S. Ghosh,[56] K. Mondal,[56] S. Nandan,[56] A. Purohit,[56] P. K. Rout,[56] A. Roy,[56] S. Roy Chowdhury,[56] G. Saha,[56] S. Sarkar,[56] M. Sharan,[56] B. Singh,[56,z] S. Thakur,[56,z] P. K. Behera,[57] R. Chudasama,[58] D. Dutta,[58] V. Jha,[58] V. Kumar,[58] P. K. Netrakanti,[58] L. M. Pant,[58] P. Shukla,[58] T. Aziz,[59] M. A. Bhat,[59] S. Dugad,[59] G. B. Mohanty,[59] N. Sur,[59] B. Sutar,[59] Ravindra Kumar Verma,[59] S. Banerjee,[60] S. Bhattacharya,[60] S. Chatterjee,[60] P. Das,[60] M. Guchait,[60] Sa. Jain,[60] S. Karmakar,[60] S. Kumar,[60] M. Maity,[60,aa] G. Majumder,[60] K. Mazumdar,[60] N. Sahoo,[60] T. Sarkar,[60,aa] S. Chauhan,[61] S. Dube,[61] V. Hegde,[61] A. Kapoor,[61] K. Kothekar,[61] S. Pandey,[61] A. Rane,[61] S. Sharma,[61] S. Chenarani,[62,bb] E. Eskandari Tadavani,[62] S. M. Etesami,[62,bb] M. Khakzad,[62] M. Mohammadi Najafabadi,[62] M. Naseri,[62] F. Rezaei Hosseinabadi,[62] B. Safarzadeh,[62,cc] M. Zeinali,[62] M. Felcini,[63] M. Grunewald,[63] M. Abbrescia,[64a,64b] C. Calabria,[64a,64b] A. Colaleo,[64a] D. Creanza,[64a,64c] L. Cristella,[64a,64b] N. De Filippis,[64a,64c] M. De Palma,[64a,64b] A. Di Florio,[64a,64b] F. Errico,[64a,64b] L. Fiore,[64a] A. Gelmi,[64a,64b] G. Iaselli,[64a,64c] M. Ince,[64a,64b] S. Lezki,[64a,64b] G. Maggi,[64a,64c] M. Maggi,[64a] G. Miniello,[64a,64b] S. My,[64a,64b] S. Nuzzo,[64a,64b] A. Pompili,[64a,64b] G. Pugliese,[64a,64c] R. Radogna,[64a] A. Ranieri,[64a] G. Selvaggi,[64a,64b] A. Sharma,[64a] L. Silvestris,[64a] R. Venditti,[64a] P. Verwilligen,[64a] G. Zito,[64a] G. Abbiendi,[65a] C. Battilana,[65a,65b] D. Bonacorsi,[65a,65b] L. Borgonovi,[65a,65b] S. Braibant-Giacomelli,[65a,65b] R. Campanini,[65a,65b] P. Capiluppi,[65a,65b] A. Castro,[65a,65b] F. R. Cavallo,[65a] S. S. Chhibra,[65a,65b] C. Ciocca,[65a] G. Codispoti,[65a,65b] M. Cuffiani,[65a,65b] G. M. Dallavalle,[65a] F. Fabbri,[65a] A. Fanfani,[65a,65b] E. Fontanesi,[65a] P. Giacomelli,[65a] C. Grandi,[65a] L. Guiducci,[65a,65b] F. Iemmi,[65a,65b] S. Lo Meo,[65a] S. Marcellini,[65a] G. Masetti,[65a] A. Montanari,[65a] F. L. Navarria,[65a,65b] A. Perrotta,[65a] F. Primavera,[65a,65b,q] T. Rovelli,[65a,65b] G. P. Siroli,[65a,65b] N. Tosi,[65a] S. Albergo,[66a,66b] A. Di Mattia,[66a] R. Potenza,[66a,66b] A. Tricomi,[66a,66b] C. Tuve,[66a,66b] G. Barbagli,[67a] K. Chatterjee,[67a,67b] V. Ciulli,[67a,67b] C. Civinini,[67a] R. D'Alessandro,[67a,67b] E. Focardi,[67a,67b] G. Latino,[67a] P. Lenzi,[67a,67b] M. Meschini,[67a] S. Paoletti,[67a] L. Russo,[67a,dd] G. Sguazzoni,[67a] D. Strom,[67a] L. Viliani,[67a] L. Benussi,[68] S. Bianco,[68] F. Fabbri,[68] D. Piccolo,[68] F. Ferro,[69a] F. Ravera,[69a,69b] E. Robutti,[69a] S. Tosi,[69a,69b] A. Benaglia,[70a] A. Beschi,[70a,70b] F. Brivio,[70a,70b] V. Ciriolo,[70a,70b,q] S. Di Guida,[70a,q] M. E. Dinardo,[70a,70b] S. Fiorendi,[70a,70b] S. Gennai,[70a] A. Ghezzi,[70a,70b] P. Govoni,[70a,70b] M. Malberti,[70a,70b] S. Malvezzi,[70a] A. Massironi,[70a,70b] D. Menasce,[70a] F. Monti,[70a] L. Moroni,[70a] M. Paganoni,[70a,70b] D. Pedrini,[70a] S. Ragazzi,[70a,70b] T. Tabarelli de Fatis,[70a,70b] D. Zuolo,[70a,70b] S. Buontempo,[71a] N. Cavallo,[71a,71c] A. De Iorio,[71a,71b] A. Di Crescenzo,[71a,71b] F. Fabozzi,[71a,71c] F. Fienga,[71a] G. Galati,[71a] A. O. M. Iorio,[71a,71b] W. A. Khan,[71a] L. Lista,[71a] S. Meola,[71a,71d,q] P. Paolucci,[71a,q] C. Sciacca,[71a,71b] E. Voevodina,[71a,71b] P. Azzi,[72a] N. Bacchetta,[72a] D. Bisello,[72a,72b] A. Boletti,[72a,72b] A. Bragagnolo,[72a] R. Carlin,[72a,72b] P. Checchia,[72a] M. Dall'Osso,[72a,72b] P. De Castro Manzano,[72a] T. Dorigo,[72a] U. Dosselli,[72a] F. Gasparini,[72a,72b] U. Gasparini,[72a,72b] A. Gozzelino,[72a] S. Y. Hoh,[72a] S. Lacaprara,[72a] P. Lujan,[72a] M. Margoni,[72a,72b] A. T. Meneguzzo,[72a,72b] J. Pazzini,[72a,72b] P. Ronchese,[72a,72b] R. Rossin,[72a,72b] F. Simonetto,[72a,72b] A. Tiko,[72a] E. Torassa,[72a] M. Zanetti,[72a,72b] P. Zotto,[72a,72b] G. Zumerle,[72a,72b] A. Braghieri,[73a] A. Magnani,[73a] P. Montagna,[73a,73b] S. P. Ratti,[73a,73b] V. Re,[73a] M. Ressegotti,[73a,73b] C. Riccardi,[73a,73b] P. Salvini,[73a] I. Vai,[73a,73b] P. Vitulo,[73a,73b] M. Biasini,[74a,74b] G. M. Bilei,[74a] C. Cecchi,[74a,74b] D. Ciangottini,[74a,74b] L. Fanò,[74a,74b] P. Lariccia,[74a,74b] R. Leonardi,[74a,74b] E. Manoni,[74a] G. Mantovani,[74a,74b] V. Mariani,[74a,74b] M. Menichelli,[74a] A. Rossi,[74a,74b] A. Santocchia,[74a,74b] D. Spiga,[74a] K. Androsov,[75a] P. Azzurri,[75a] G. Bagliesi,[75a] L. Bianchini,[75a] T. Boccali,[75a] L. Borrello,[75a] R. Castaldi,[75a] M. A. Ciocci,[75a,75b] R. Dell'Orso,[75a] G. Fedi,[75a] F. Fiori,[75a,75c] L. Giannini,[75a,75c] A. Giassi,[75a] M. T. Grippo,[75a] F. Ligabue,[75a,75c] E. Manca,[75a,75c] G. Mandorli,[75a,75c] A. Messineo,[75a,75b] F. Palla,[75a] A. Rizzi,[75a,75b] P. Spagnolo,[75a] R. Tenchini,[75a] G. Tonelli,[75a,75b] A. Venturi,[75a] P. G. Verdini,[75a] L. Barone,[76a,76b] F. Cavallari,[76a] M. Cipriani,[76a,76b] D. Del Re,[76a,76b] E. Di Marco,[76a,76b] M. Diemoz,[76a] S. Gelli,[76a,76b] E. Longo,[76a,76b] B. Marzocchi,[76a,76b] P. Meridiani,[76a] G. Organtini,[76a,76b] F. Pandolfi,[76a] R. Paramatti,[76a,76b] F. Preiato,[76a,76b] S. Rahatlou,[76a,76b] C. Rovelli,[76a] F. Santanastasio,[76a,76b] N. Amapane,[77a,77b] R. Arcidiacono,[77a,77c] S. Argiro,[77a,77b] M. Arneodo,[77a,77c] N. Bartosik,[77a] R. Bellan,[77a,77b] C. Biino,[77a] N. Cartiglia,[77a] F. Cenna,[77a,77b] S. Cometti,[77a] M. Costa,[77a,77b] R. Covarelli,[77a,77b] N. Demaria,[77a] B. Kiani,[77a,77b] C. Mariotti,[77a] S. Maselli,[77a] E. Migliore,[77a,77b] V. Monaco,[77a,77b] E. Monteil,[77a,77b] M. Monteno,[77a] M. M. Obertino,[77a,77b] L. Pacher,[77a,77b] N. Pastrone,[77a] M. Pelliccioni,[77a] G. L. Pinna Angioni,[77a,77b] A. Romero,[77a,77b] M. Ruspa,[77a,77c] R. Sacchi,[77a,77b] K. Shchelina,[77a,77b] V. Sola,[77a] A. Solano,[77a,77b] D. Soldi,[77a,77b] A. Staiano,[77a] S. Belforte,[78a] V. Candelise,[78a,78b] M. Casarsa,[78a] F. Cossutti,[78a] A. Da Rold,[78a,78b] G. Della Ricca,[78a,78b] F. Vazzoler,[78a,78b] A. Zanetti,[78a] D. H. Kim,[79] G. N. Kim,[79] M. S. Kim,[79] J. Lee,[79] S. Lee,[79] S. W. Lee,[79] C. S. Moon,[79] Y. D. Oh,[79] S. I. Pak,[79] S. Sekmen,[79] D. C. Son,[79] Y. C. Yang,[79] H. Kim,[80] D. H. Moon,[80] G. Oh,[80] B. Francois,[81] J. Goh,[81,ee] T. J. Kim,[81] S. Cho,[82] S. Choi,[82] Y. Go,[82] D. Gyun,[82] S. Ha,[82] B. Hong,[82] Y. Jo,[82] K. Lee,[82] K. S. Lee,[82] S. Lee,[82] J. Lim,[82]

S. K. Park,[82] Y. Roh,[82] H. S. Kim,[83] J. Almond,[84] J. Kim,[84] J. S. Kim,[84] H. Lee,[84] K. Lee,[84] K. Nam,[84] S. B. Oh,[84] B. C. Radburn-Smith,[84] S. h. Seo,[84] U. K. Yang,[84] H. D. Yoo,[84] G. B. Yu,[84] D. Jeon,[85] H. Kim,[85] J. H. Kim,[85] J. S. H. Lee,[85] I. C. Park,[85] Y. Choi,[86] C. Hwang,[86] J. Lee,[86] I. Yu,[86] V. Dudenas,[87] A. Juodagalvis,[87] J. Vaitkus,[87] I. Ahmed,[88] Z. A. Ibrahim,[88] M. A. B. Md Ali,[88,ff] F. Mohamad Idris,[88,gg] W. A. T. Wan Abdullah,[88] M. N. Yusli,[88] Z. Zolkapli,[88] J. F. Benitez,[89] A. Castaneda Hernandez,[89] J. A. Murillo Quijada,[89] H. Castilla-Valdez,[90] E. De La Cruz-Burelo,[90] M. C. Duran-Osuna,[90] I. Heredia-De La Cruz,[90,hh] R. Lopez-Fernandez,[90] J. Mejia Guisao,[90] R. I. Rabadan-Trejo,[90] M. Ramirez-Garcia,[90] G. Ramirez-Sanchez,[90] R Reyes-Almanza,[90] A. Sanchez-Hernandez,[90] S. Carrillo Moreno,[91] C. Oropeza Barrera,[91] F. Vazquez Valencia,[91] J. Eysermans,[92] I. Pedraza,[92] H. A. Salazar Ibarguen,[92] C. Uribe Estrada,[92] A. Morelos Pineda,[93] D. Krofcheck,[94] S. Bheesette,[95] P. H. Butler,[95] A. Ahmad,[96] M. Ahmad,[96] M. I. Asghar,[96] Q. Hassan,[96] H. R. Hoorani,[96] A. Saddique,[96] M. A. Shah,[96] M. Shoaib,[96] M. Waqas,[96] H. Bialkowska,[97] M. Bluj,[97] B. Boimska,[97] T. Frueboes,[97] M. Górski,[97] M. Kazana,[97] M. Szleper,[97] P. Traczyk,[97] P. Zalewski,[97] K. Bunkowski,[98] A. Byszuk,[98,ii] K. Doroba,[98] A. Kalinowski,[98] M. Konecki,[98] J. Krolikowski,[98] M. Misiura,[98] M. Olszewski,[98] A. Pyskir,[98] M. Walczak,[98] M. Araujo,[99] P. Bargassa,[99] C. Beirão Da Cruz E Silva,[99] A. Di Francesco,[99] P. Faccioli,[99] B. Galinhas,[99] M. Gallinaro,[99] J. Hollar,[99] N. Leonardo,[99] M. V. Nemallapudi,[99] J. Seixas,[99] G. Strong,[99] O. Toldaiev,[99] D. Vadruccio,[99] J. Varela,[99] S. Afanasiev,[100] P. Bunin,[100] M. Gavrilenko,[100] I. Golutvin,[100] I. Gorbunov,[100] A. Kamenev,[100] V. Karjavine,[100] A. Lanev,[100] A. Malakhov,[100] V. Matveev,[100,jj,kk] P. Moisenz,[100] V. Palichik,[100] V. Perelygin,[100] S. Shmatov,[100] S. Shulha,[100] N. Skatchkov,[100] V. Smirnov,[100] N. Voytishin,[100] A. Zarubin,[100] V. Golovtsov,[101] Y. Ivanov,[101] V. Kim,[101,ll] E. Kuznetsova,[101,mm] P. Levchenko,[101] V. Murzin,[101] V. Oreshkin,[101] I. Smirnov,[101] D. Sosnov,[101] V. Sulimov,[101] L. Uvarov,[101] S. Vavilov,[101] A. Vorobyev,[101] Yu. Andreev,[102] A. Dermenev,[102] S. Gninenko,[102] N. Golubev,[102] A. Karneyeu,[102] M. Kirsanov,[102] N. Krasnikov,[102] A. Pashenkov,[102] D. Tlisov,[102] A. Toropin,[102] V. Epshteyn,[103] V. Gavrilov,[103] N. Lychkovskaya,[103] V. Popov,[103] I. Pozdnyakov,[103] G. Safronov,[103] A. Spiridonov,[103] A. Stepennov,[103] V. Stolin,[103] M. Toms,[103] E. Vlasov,[103] A. Zhokin,[103] T. Aushev,[104] M. Chadeeva,[105,nn] R. Chistov,[105,nn] M. Danilov,[105,nn] P. Parygin,[105] D. Philippov,[105] S. Polikarpov,[105,nn] V. Andreev,[106] M. Azarkin,[106] I. Dremin,[106,kk] M. Kirakosyan,[106] S. V. Rusakov,[106] A. Terkulov,[106] A. Baskakov,[107] A. Belyaev,[107] E. Boos,[107] A. Ershov,[107] A. Gribushin,[107] A. Kaminskiy,[107,oo] O. Kodolova,[107] V. Korotkikh,[107] I. Lokhtin,[107] I. Miagkov,[107] S. Obraztsov,[107] S. Petrushanko,[107] V. Savrin,[107] A. Snigirev,[107] I. Vardanyan,[107] A. Barnyakov,[108,pp] V. Blinov,[108,pp] T. Dimova,[108,pp] L. Kardapoltsev,[108,pp] Y. Skovpen,[108,pp] I. Azhgirey,[109] I. Bayshev,[109] S. Bitioukov,[109] D. Elumakhov,[109] A. Godizov,[109] V. Kachanov,[109] A. Kalinin,[109] D. Konstantinov,[109] P. Mandrik,[109] V. Petrov,[109] R. Ryutin,[109] S. Slabospitskii,[109] A. Sobol,[109] S. Troshin,[109] N. Tyurin,[109] A. Uzunian,[109] A. Volkov,[109] A. Babaev,[110] S. Baidali,[110] V. Okhotnikov,[110] P. Adzic,[111,qq] P. Cirkovic,[111] D. Devetak,[111] M. Dordevic,[111] J. Milosevic,[111] J. Alcaraz Maestre,[112] A. Álvarez Fernández,[112] I. Bachiller,[112] M. Barrio Luna,[112] J. A. Brochero Cifuentes,[112] M. Cerrada,[112] N. Colino,[112] B. De La Cruz,[112] A. Delgado Peris,[112] C. Fernandez Bedoya,[112] J. P. Fernández Ramos,[112] J. Flix,[112] M. C. Fouz,[112] O. Gonzalez Lopez,[112] S. Goy Lopez,[112] J. M. Hernandez,[112] M. I. Josa,[112] D. Moran,[112] A. Pérez-Calero Yzquierdo,[112] J. Puerta Pelayo,[112] I. Redondo,[112] L. Romero,[112] M. S. Soares,[112] A. Triossi,[112] C. Albajar,[113] J. F. de Trocóniz,[113] J. Cuevas,[114] C. Erice,[114] J. Fernandez Menendez,[114] S. Folgueras,[114] I. Gonzalez Caballero,[114] J. R. González Fernández,[114] E. Palencia Cortezon,[114] V. Rodríguez Bouza,[114] S. Sanchez Cruz,[114] P. Vischia,[114] J. M. Vizan Garcia,[114] I. J. Cabrillo,[115] A. Calderon,[115] B. Chazin Quero,[115] J. Duarte Campderros,[115] M. Fernandez,[115] P. J. Fernández Manteca,[115] A. García Alonso,[115] J. Garcia-Ferrero,[115] G. Gomez,[115] A. Lopez Virto,[115] J. Marco,[115] C. Martinez Rivero,[115] P. Martinez Ruiz del Arbol,[115] F. Matorras,[115] J. Piedra Gomez,[115] C. Prieels,[115] T. Rodrigo,[115] A. Ruiz-Jimeno,[115] L. Scodellaro,[115] N. Trevisani,[115] I. Vila,[115] R. Vilar Cortabitarte,[115] N. Wickramage,[116] D. Abbaneo,[117] B. Akgun,[117] E. Auffray,[117] G. Auzinger,[117] P. Baillon,[117] A. H. Ball,[117] D. Barney,[117] J. Bendavid,[117] M. Bianco,[117] A. Bocci,[117] C. Botta,[117] E. Brondolin,[117] T. Camporesi,[117] M. Cepeda,[117] G. Cerminara,[117] E. Chapon,[117] Y. Chen,[117] G. Cucciati,[117] D. d'Enterria,[117] A. Dabrowski,[117] N. Daci,[117] V. Daponte,[117] A. David,[117] A. De Roeck,[117] N. Deelen,[117] M. Dobson,[117] M. Dünser,[117] N. Dupont,[117] A. Elliott-Peisert,[117] P. Everaerts,[117] F. Fallavollita,[117,rr] D. Fasanella,[117] G. Franzoni,[117] J. Fulcher,[117] W. Funk,[117] D. Gigi,[117] A. Gilbert,[117] K. Gill,[117] F. Glege,[117] M. Guilbaud,[117] D. Gulhan,[117] J. Hegeman,[117] C. Heidegger,[117] V. Innocente,[117] A. Jafari,[117] P. Janot,[117] O. Karacheban,[117,t] J. Kieseler,[117] A. Kornmayer,[117] M. Krammer,[117,b] C. Lange,[117] P. Lecoq,[117] C. Lourenço,[117] L. Malgeri,[117] M. Mannelli,[117] F. Meijers,[117] J. A. Merlin,[117] S. Mersi,[117] E. Meschi,[117] P. Milenovic,[117,ss] F. Moortgat,[117] M. Mulders,[117] J. Ngadiuba,[117] S. Nourbakhsh,[117] S. Orfanelli,[117] L. Orsini,[117] F. Pantaleo,[117,q] L. Pape,[117] E. Perez,[117] M. Peruzzi,[117] A. Petrilli,[117] G. Petrucciani,[117] A. Pfeiffer,[117] M. Pierini,[117]

F. M. Pitters,[117] D. Rabady,[117] A. Racz,[117] T. Reis,[117] G. Rolandi,[117,tt] M. Rovere,[117] H. Sakulin,[117] C. Schäfer,[117] C. Schwick,[117] M. Seidel,[117] M. Selvaggi,[117] A. Sharma,[117] P. Silva,[117] P. Sphicas,[117,uu] A. Stakia,[117] J. Steggemann,[117] M. Tosi,[117] D. Treille,[117] A. Tsirou,[117] V. Veckalns,[117,vv] M. Verzetti,[117] W. D. Zeuner,[117] L. Caminada,[118,ww] K. Deiters,[118] W. Erdmann,[118] R. Horisberger,[118] Q. Ingram,[118] H. C. Kaestli,[118] D. Kotlinski,[118] U. Langenegger,[118] T. Rohe,[118] S. A. Wiederkehr,[118] M. Backhaus,[119] L. Bäni,[119] P. Berger,[119] N. Chernyavskaya,[119] G. Dissertori,[119] M. Dittmar,[119] M. Donegà,[119] C. Dorfer,[119] T. A. Gómez Espinosa,[119] C. Grab,[119] D. Hits,[119] T. Klijnsma,[119] W. Lustermann,[119] R. A. Manzoni,[119] M. Marionneau,[119] M. T. Meinhard,[119] F. Micheli,[119] P. Musella,[119] F. Nessi-Tedaldi,[119] J. Pata,[119] F. Pauss,[119] G. Perrin,[119] L. Perrozzi,[119] S. Pigazzini,[119] M. Quittnat,[119] C. Reissel,[119] D. Ruini,[119] D. A. Sanz Becerra,[119] M. Schönenberger,[119] L. Shchutska,[119] V. R. Tavolaro,[119] K. Theofilatos,[119] M. L. Vesterbacka Olsson,[119] R. Wallny,[119] D. H. Zhu,[119] T. K. Aarrestad,[120] C. Amsler,[120,xx] D. Brzhechko,[120] M. F. Canelli,[120] A. De Cosa,[120] R. Del Burgo,[120] S. Donato,[120] C. Galloni,[120] T. Hreus,[120] B. Kilminster,[120] S. Leontsinis,[120] I. Neutelings,[120] G. Rauco,[120] P. Robmann,[120] D. Salerno,[120] K. Schweiger,[120] C. Seitz,[120] Y. Takahashi,[120] A. Zucchetta,[120] Y. H. Chang,[121] K. y. Cheng,[121] T. H. Doan,[121] R. Khurana,[121] C. M. Kuo,[121] W. Lin,[121] A. Pozdnyakov,[121] S. S. Yu,[121] P. Chang,[122] Y. Chao,[122] K. F. Chen,[122] P. H. Chen,[122] W.-S. Hou,[122] Arun Kumar,[122] Y. F. Liu,[122] R.-S. Lu,[122] E. Paganis,[122] A. Psallidas,[122] A. Steen,[122] B. Asavapibhop,[123] N. Srimanobhas,[123] N. Suwonjandee,[123] M. N. Bakirci,[124,yy] A. Bat,[124] F. Boran,[124] S. Cerci,[124,zz] S. Damarseckin,[124] Z. S. Demiroglu,[124] F. Dolek,[124] C. Dozen,[124] I. Dumanoglu,[124] E. Eskut,[124] S. Girgis,[124] G. Gokbulut,[124] Y. Guler,[124] E. Gurpinar,[124] I. Hos,[124,aaa] C. Isik,[124] E. E. Kangal,[124,bbb] O. Kara,[124] U. Kiminsu,[124] M. Oglakci,[124] G. Onengut,[124] K. Ozdemir,[124,ccc] A. Polatoz,[124] D. Sunar Cerci,[124,zz] U. G. Tok,[124] S. Turkcapar,[124] I. S. Zorbakir,[124] C. Zorbilmez,[124] B. Isildak,[125,ddd] G. Karapinar,[125,eee] M. Yalvac,[125] M. Zeyrek,[125] I. O. Atakisi,[126] E. Gülmez,[126] M. Kaya,[126,fff] O. Kaya,[126,ggg] S. Ozkorucuklu,[126,hhh] S. Tekten,[126] E. A. Yetkin,[126,iii] M. N. Agaras,[127] A. Cakir,[127] K. Cankocak,[127] Y. Komurcu,[127] S. Sen,[127,jjj] B. Grynyov,[128] L. Levchuk,[129] F. Ball,[130] L. Beck,[130] J. J. Brooke,[130] D. Burns,[130] E. Clement,[130] D. Cussans,[130] O. Davignon,[130] H. Flacher,[130] J. Goldstein,[130] G. P. Heath,[130] H. F. Heath,[130] L. Kreczko,[130] D. M. Newbold,[130,kkk] S. Paramesvaran,[130] B. Penning,[130] T. Sakuma,[130] D. Smith,[130] V. J. Smith,[130] J. Taylor,[130] A. Titterton,[130] A. Belyaev,[131,lll] C. Brew,[131] R. M. Brown,[131] D. Cieri,[131] D. J. A. Cockerill,[131] J. A. Coughlan,[131] K. Harder,[131] S. Harper,[131] J. Linacre,[131] E. Olaiya,[131] D. Petyt,[131] C. H. Shepherd-Themistocleous,[131] A. Thea,[131] I. R. Tomalin,[131] T. Williams,[131] W. J. Womersley,[131] R. Bainbridge,[132] P. Bloch,[132] J. Borg,[132] S. Breeze,[132] O. Buchmuller,[132] A. Bundock,[132] D. Colling,[132] P. Dauncey,[132] G. Davies,[132] M. Della Negra,[132] R. Di Maria,[132] Y. Haddad,[132] G. Hall,[132] G. Iles,[132] T. James,[132] M. Komm,[132] C. Laner,[132] L. Lyons,[132] A.-M. Magnan,[132] S. Malik,[132] A. Martelli,[132] J. Nash,[132,mmm] A. Nikitenko,[132,h] V. Palladino,[132] M. Pesaresi,[132] D. M. Raymond,[132] A. Richards,[132] A. Rose,[132] E. Scott,[132] C. Seez,[132] A. Shtipliyski,[132] G. Singh,[132] M. Stoye,[132] T. Strebler,[132] S. Summers,[132] A. Tapper,[132] K. Uchida,[132] T. Virdee,[132,q] N. Wardle,[132] D. Winterbottom,[132] J. Wright,[132] S. C. Zenz,[132] J. E. Cole,[133] P. R. Hobson,[133] A. Khan,[133] P. Kyberd,[133] C. K. Mackay,[133] A. Morton,[133] I. D. Reid,[133] L. Teodorescu,[133] S. Zahid,[133] K. Call,[134] J. Dittmann,[134] K. Hatakeyama,[134] H. Liu,[134] C. Madrid,[134] B. Mcmaster,[134] N. Pastika,[134] C. Smith,[134] R. Bartek,[135] A. Dominguez,[135] A. Buccilli,[136] S. I. Cooper,[136] C. Henderson,[136] P. Rumerio,[136] C. West,[136] D. Arcaro,[137] T. Bose,[137] D. Gastler,[137] D. Pinna,[137] D. Rankin,[137] C. Richardson,[137] J. Rohlf,[137] L. Sulak,[137] D. Zou,[137] G. Benelli,[138] X. Coubez,[138] D. Cutts,[138] M. Hadley,[138] J. Hakala,[138] U. Heintz,[138] J. M. Hogan,[138,nnn] K. H. M. Kwok,[138] E. Laird,[138] G. Landsberg,[138] J. Lee,[138] Z. Mao,[138] M. Narain,[138] S. Sagir,[138,ooo] R. Syarif,[138] E. Usai,[138] D. Yu,[138] R. Band,[139] C. Brainerd,[139] R. Breedon,[139] D. Burns,[139] M. Calderon De La Barca Sanchez,[139] M. Chertok,[139] J. Conway,[139] R. Conway,[139] P. T. Cox,[139] R. Erbacher,[139] C. Flores,[139] G. Funk,[139] W. Ko,[139] O. Kukral,[139] R. Lander,[139] M. Mulhearn,[139] D. Pellett,[139] J. Pilot,[139] S. Shalhout,[139] M. Shi,[139] D. Stolp,[139] D. Taylor,[139] K. Tos,[139] M. Tripathi,[139] Z. Wang,[139] F. Zhang,[139] M. Bachtis,[140] C. Bravo,[140] R. Cousins,[140] A. Dasgupta,[140] A. Florent,[140] J. Hauser,[140] M. Ignatenko,[140] N. Mccoll,[140] S. Regnard,[140] D. Saltzberg,[140] C. Schnaible,[140] V. Valuev,[140] E. Bouvier,[141] K. Burt,[141] R. Clare,[141] J. W. Gary,[141] S. M. A. Ghiasi Shirazi,[141] G. Hanson,[141] G. Karapostoli,[141] E. Kennedy,[141] F. Lacroix,[141] O. R. Long,[141] M. Olmedo Negrete,[141] M. I. Paneva,[141] W. Si,[141] L. Wang,[141] H. Wei,[141] S. Wimpenny,[141] B. R. Yates,[141] J. G. Branson,[142] P. Chang,[142] S. Cittolin,[142] M. Derdzinski,[142] R. Gerosa,[142] D. Gilbert,[142] B. Hashemi,[142] A. Holzner,[142] D. Klein,[142] G. Kole,[142] V. Krutelyov,[142] J. Letts,[142] M. Masciovecchio,[142] D. Olivito,[142] S. Padhi,[142] M. Pieri,[142] M. Sani,[142] V. Sharma,[142] S. Simon,[142] M. Tadel,[142] A. Vartak,[142] S. Wasserbaech,[142,ppp] J. Wood,[142] F. Würthwein,[142] A. Yagil,[142] G. Zevi Della Porta,[142] N. Amin,[143] R. Bhandari,[143] J. Bradmiller-Feld,[143] C. Campagnari,[143] M. Citron,[143] A. Dishaw,[143] V. Dutta,[143] M. Franco Sevilla,[143] L. Gouskos,[143] R. Heller,[143] J. Incandela,[143] A. Ovcharova,[143] H. Qu,[143] J. Richman,[143]

D. Stuart,[143] I. Suarez,[143] S. Wang,[143] J. Yoo,[143] D. Anderson,[144] A. Bornheim,[144] J. M. Lawhorn,[144] H. B. Newman,[144] T. Q. Nguyen,[144] M. Spiropulu,[144] J. R. Vlimant,[144] R. Wilkinson,[144] S. Xie,[144] Z. Zhang,[144] R. Y. Zhu,[144] M. B. Andrews,[145] T. Ferguson,[145] T. Mudholkar,[145] M. Paulini,[145] M. Sun,[145] I. Vorobiev,[145] M. Weinberg,[145] J. P. Cumalat,[146] W. T. Ford,[146] F. Jensen,[146] A. Johnson,[146] M. Krohn,[146] E. MacDonald,[146] T. Mulholland,[146] R. Patel,[146] A. Perloff,[146] K. Stenson,[146] K. A. Ulmer,[146] S. R. Wagner,[146] J. Alexander,[147] J. Chaves,[147] Y. Cheng,[147] J. Chu,[147] A. Datta,[147] K. Mcdermott,[147] N. Mirman,[147] J. R. Patterson,[147] D. Quach,[147] A. Rinkevicius,[147] A. Ryd,[147] L. Skinnari,[147] L. Soffi,[147] S. M. Tan,[147] Z. Tao,[147] J. Thom,[147] J. Tucker,[147] P. Wittich,[147] M. Zientek,[147] S. Abdullin,[148] M. Albrow,[148] M. Alyari,[148] G. Apollinari,[148] A. Apresyan,[148] A. Apyan,[148] S. Banerjee,[148] L. A. T. Bauerdick,[148] A. Beretvas,[148] J. Berryhill,[148] P. C. Bhat,[148] K. Burkett,[148] J. N. Butler,[148] A. Canepa,[148] G. B. Cerati,[148] H. W. K. Cheung,[148] F. Chlebana,[148] M. Cremonesi,[148] J. Duarte,[148] V. D. Elvira,[148] J. Freeman,[148] Z. Gecse,[148] E. Gottschalk,[148] L. Gray,[148] D. Green,[148] S. Grünendahl,[148] O. Gutsche,[148] J. Hanlon,[148] R. M. Harris,[148] S. Hasegawa,[148] J. Hirschauer,[148] Z. Hu,[148] B. Jayatilaka,[148] S. Jindariani,[148] M. Johnson,[148] U. Joshi,[148] B. Klima,[148] M. J. Kortelainen,[148] B. Kreis,[148] S. Lammel,[148] D. Lincoln,[148] R. Lipton,[148] M. Liu,[148] T. Liu,[148] J. Lykken,[148] K. Maeshima,[148] J. M. Marraffino,[148] D. Mason,[148] P. McBride,[148] P. Merkel,[148] S. Mrenna,[148] S. Nahn,[148] V. O'Dell,[148] K. Pedro,[148] C. Pena,[148] O. Prokofyev,[148] G. Rakness,[148] L. Ristori,[148] A. Savoy-Navarro,[148,qqq] B. Schneider,[148] E. Sexton-Kennedy,[148] A. Soha,[148] W. J. Spalding,[148] L. Spiegel,[148] S. Stoynev,[148] J. Strait,[148] N. Strobbe,[148] L. Taylor,[148] S. Tkaczyk,[148] N. V. Tran,[148] L. Uplegger,[148] E. W. Vaandering,[148] C. Vernieri,[148] M. Verzocchi,[148] R. Vidal,[148] M. Wang,[148] H. A. Weber,[148] A. Whitbeck,[148] D. Acosta,[149] P. Avery,[149] P. Bortignon,[149] D. Bourilkov,[149] A. Brinkerhoff,[149] L. Cadamuro,[149] A. Carnes,[149] M. Carver,[149] D. Curry,[149] R. D. Field,[149] S. V. Gleyzer,[149] B. M. Joshi,[149] J. Konigsberg,[149] A. Korytov,[149] K. H. Lo,[149] P. Ma,[149] K. Matchev,[149] H. Mei,[149] G. Mitselmakher,[149] D. Rosenzweig,[149] K. Shi,[149] D. Sperka,[149] J. Wang,[149] S. Wang,[149] X. Zuo,[149] Y. R. Joshi,[150] S. Linn,[150] A. Ackert,[151] T. Adams,[151] A. Askew,[151] S. Hagopian,[151] V. Hagopian,[151] K. F. Johnson,[151] T. Kolberg,[151] G. Martinez,[151] T. Perry,[151] H. Prosper,[151] A. Saha,[151] C. Schiber,[151] R. Yohay,[151] M. M. Baarmand,[152] V. Bhopatkar,[152] S. Colafranceschi,[152] M. Hohlmann,[152] D. Noonan,[152] M. Rahmani,[152] T. Roy,[152] F. Yumiceva,[152] M. R. Adams,[153] L. Apanasevich,[153] D. Berry,[153] R. R. Betts,[153] R. Cavanaugh,[153] X. Chen,[153] S. Dittmer,[153] O. Evdokimov,[153] C. E. Gerber,[153] D. A. Hangal,[153] D. J. Hofman,[153] K. Jung,[153] J. Kamin,[153] C. Mills,[153] I. D. Sandoval Gonzalez,[153] M. B. Tonjes,[153] H. Trauger,[153] N. Varelas,[153] H. Wang,[153] X. Wang,[153] Z. Wu,[153] J. Zhang,[153] M. Alhusseini,[154] B. Bilki,[154,rrr] W. Clarida,[154] K. Dilsiz,[154,sss] S. Durgut,[154] R. P. Gandrajula,[154] M. Haytmyradov,[154] V. Khristenko,[154] J.-P. Merlo,[154] A. Mestvirishvili,[154] A. Moeller,[154] J. Nachtman,[154] H. Ogul,[154,ttt] Y. Onel,[154] F. Ozok,[154,uuu] A. Penzo,[154] C. Snyder,[154] E. Tiras,[154] J. Wetzel,[154] B. Blumenfeld,[155] A. Cocoros,[155] N. Eminizer,[155] D. Fehling,[155] L. Feng,[155] A. V. Gritsan,[155] W. T. Hung,[155] P. Maksimovic,[155] J. Roskes,[155] U. Sarica,[155] M. Swartz,[155] M. Xiao,[155] C. You,[155] A. Al-bataineh,[156] P. Baringer,[156] A. Bean,[156] S. Boren,[156] J. Bowen,[156] A. Bylinkin,[156] J. Castle,[156] S. Khalil,[156] A. Kropivnitskaya,[156] D. Majumder,[156] W. Mcbrayer,[156] M. Murray,[156] C. Rogan,[156] S. Sanders,[156] E. Schmitz,[156] J. D. Tapia Takaki,[156] Q. Wang,[156] S. Duric,[157] A. Ivanov,[157] K. Kaadze,[157] D. Kim,[157] Y. Maravin,[157] D. R. Mendis,[157] T. Mitchell,[157] A. Modak,[157] A. Mohammadi,[157] L. K. Saini,[157] N. Skhirtladze,[157] F. Rebassoo,[158] D. Wright,[158] A. Baden,[159] O. Baron,[159] A. Belloni,[159] S. C. Eno,[159] Y. Feng,[159] C. Ferraioli,[159] N. J. Hadley,[159] S. Jabeen,[159] G. Y. Jeng,[159] R. G. Kellogg,[159] J. Kunkle,[159] A. C. Mignerey,[159] S. Nabili,[159] F. Ricci-Tam,[159] Y. H. Shin,[159] A. Skuja,[159] S. C. Tonwar,[159] K. Wong,[159] D. Abercrombie,[160] B. Allen,[160] V. Azzolini,[160] A. Baty,[160] G. Bauer,[160] R. Bi,[160] S. Brandt,[160] W. Busza,[160] I. A. Cali,[160] M. D'Alfonso,[160] Z. Demiragli,[160] G. Gomez Ceballos,[160] M. Goncharov,[160] P. Harris,[160] D. Hsu,[160] M. Hu,[160] Y. Iiyama,[160] G. M. Innocenti,[160] M. Klute,[160] D. Kovalskyi,[160] Y.-J. Lee,[160] P. D. Luckey,[160] B. Maier,[160] A. C. Marini,[160] C. Mcginn,[160] C. Mironov,[160] S. Narayanan,[160] X. Niu,[160] C. Paus,[160] C. Roland,[160] G. Roland,[160] G. S. F. Stephans,[160] K. Sumorok,[160] K. Tatar,[160] D. Velicanu,[160] J. Wang,[160] T. W. Wang,[160] B. Wyslouch,[160] S. Zhaozhong,[160] A. C. Benvenuti,[161,a] R. M. Chatterjee,[161] A. Evans,[161] P. Hansen,[161] J. Hiltbrand,[161] Sh. Jain,[161] S. Kalafut,[161] Y. Kubota,[161] Z. Lesko,[161] J. Mans,[161] N. Ruckstuhl,[161] R. Rusack,[161] M. A. Wadud,[161] J. G. Acosta,[162] S. Oliveros,[162] E. Avdeeva,[163] K. Bloom,[163] D. R. Claes,[163] C. Fangmeier,[163] F. Golf,[163] R. Gonzalez Suarez,[163] R. Kamalieddin,[163] I. Kravchenko,[163] J. Monroy,[163] J. E. Siado,[163] G. R. Snow,[163] B. Stieger,[163] A. Godshalk,[164] C. Harrington,[164] I. Iashvili,[164] A. Kharchilava,[164] C. Mclean,[164] D. Nguyen,[164] A. Parker,[164] S. Rappoccio,[164] B. Roozbahani,[164] G. Alverson,[165] E. Barberis,[165] C. Freer,[165] A. Hortiangtham,[165] D. M. Morse,[165] T. Orimoto,[165] R. Teixeira De Lima,[165] T. Wamorkar,[165] B. Wang,[165] A. Wisecarver,[165] D. Wood,[165] S. Bhattacharya,[166] O. Charaf,[166] K. A. Hahn,[166] N. Mucia,[166] N. Odell,[166] M. H. Schmitt,[166] K. Sung,[166] M. Trovato,[166] M. Velasco,[166] R. Bucci,[167] N. Dev,[167] M. Hildreth,[167] K. Hurtado Anampa,[167] C. Jessop,[167] D. J. Karmgard,[167] N. Kellams,[167]

K. Lannon,[167] W. Li,[167] N. Loukas,[167] N. Marinelli,[167] F. Meng,[167] C. Mueller,[167] Y. Musienko,[167,jj] M. Planer,[167] A. Reinsvold,[167] R. Ruchti,[167] P. Siddireddy,[167] G. Smith,[167] S. Taroni,[167] M. Wayne,[167] A. Wightman,[167] M. Wolf,[167] A. Woodard,[167] J. Alimena,[168] L. Antonelli,[168] B. Bylsma,[168] L. S. Durkin,[168] S. Flowers,[168] B. Francis,[168] A. Hart,[168] C. Hill,[168] W. Ji,[168] T. Y. Ling,[168] W. Luo,[168] B. L. Winer,[168] S. Cooperstein,[169] P. Elmer,[169] J. Hardenbrook,[169] S. Higginbotham,[169] A. Kalogeropoulos,[169] D. Lange,[169] M. T. Lucchini,[169] J. Luo,[169] D. Marlow,[169] K. Mei,[169] I. Ojalvo,[169] J. Olsen,[169] C. Palmer,[169] P. Piroué,[169] J. Salfeld-Nebgen,[169] D. Stickland,[169] C. Tully,[169] S. Malik,[170] S. Norberg,[170] A. Barker,[171] V. E. Barnes,[171] S. Das,[171] L. Gutay,[171] M. Jones,[171] A. W. Jung,[171] A. Khatiwada,[171] B. Mahakud,[171] D. H. Miller,[171] N. Neumeister,[171] C. C. Peng,[171] S. Piperov,[171] H. Qiu,[171] J. F. Schulte,[171] J. Sun,[171] F. Wang,[171] R. Xiao,[171] W. Xie,[171] T. Cheng,[172] J. Dolen,[172] N. Parashar,[172] Z. Chen,[173] K. M. Ecklund,[173] S. Freed,[173] F. J. M. Geurts,[173] M. Kilpatrick,[173] W. Li,[173] B. P. Padley,[173] R. Redjimi,[173] J. Roberts,[173] J. Rorie,[173] W. Shi,[173] Z. Tu,[173] J. Zabel,[173] A. Zhang,[173] A. Bodek,[174] P. de Barbaro,[174] R. Demina,[174] Y. t. Duh,[174] J. L. Dulemba,[174] C. Fallon,[174] T. Ferbel,[174] M. Galanti,[174] A. Garcia-Bellido,[174] J. Han,[174] O. Hindrichs,[174] A. Khukhunaishvili,[174] P. Tan,[174] R. Taus,[174] A. Agapitos,[175] J. P. Chou,[175] Y. Gershtein,[175] E. Halkiadakis,[175] M. Heindl,[175] E. Hughes,[175] S. Kaplan,[175] R. Kunnawalkam Elayavalli,[175] S. Kyriacou,[175] A. Lath,[175] R. Montalvo,[175] K. Nash,[175] M. Osherson,[175] H. Saka,[175] S. Salur,[175] S. Schnetzer,[175] D. Sheffield,[175] S. Somalwar,[175] R. Stone,[175] S. Thomas,[175] P. Thomassen,[175] M. Walker,[175] A. G. Delannoy,[176] J. Heideman,[176] G. Riley,[176] S. Spanier,[176] O. Bouhali,[177,vvv] A. Celik,[177] M. Dalchenko,[177] M. De Mattia,[177] A. Delgado,[177] S. Dildick,[177] R. Eusebi,[177] J. Gilmore,[177] T. Huang,[177] T. Kamon,[177,www] S. Luo,[177] R. Mueller,[177] D. Overton,[177] L. Perniè,[177] D. Rathjens,[177] A. Safonov,[177] N. Akchurin,[178] J. Damgov,[178] F. De Guio,[178] P. R. Dudero,[178] S. Kunori,[178] K. Lamichhane,[178] S. W. Lee,[178] T. Mengke,[178] S. Muthumuni,[178] T. Peltola,[178] S. Undleeb,[178] I. Volobouev,[178] Z. Wang,[178] S. Greene,[179] A. Gurrola,[179] R. Janjam,[179] W. Johns,[179] C. Maguire,[179] A. Melo,[179] H. Ni,[179] K. Padeken,[179] J. D. Ruiz Alvarez,[179] P. Sheldon,[179] S. Tuo,[179] J. Velkovska,[179] M. Verweij,[179] Q. Xu,[179] M. W. Arenton,[180] P. Barria,[180] B. Cox,[180] R. Hirosky,[180] M. Joyce,[180] A. Ledovskoy,[180] H. Li,[180] C. Neu,[180] T. Sinthuprasith,[180] Y. Wang,[180] E. Wolfe,[180] F. Xia,[180] R. Harr,[181] P. E. Karchin,[181] N. Poudyal,[181] J. Sturdy,[181] P. Thapa,[181] S. Zaleski,[181] M. Brodski,[182] J. Buchanan,[182] C. Caillol,[182] D. Carlsmith,[182] S. Dasu,[182] L. Dodd,[182] B. Gomber,[182] M. Grothe,[182] M. Herndon,[182] A. Hervé,[182] U. Hussain,[182] P. Klabbers,[182] A. Lanaro,[182] K. Long,[182] R. Loveless,[182] T. Ruggles,[182] A. Savin,[182] V. Sharma,[182] N. Smith,[182] W. H. Smith,[182] and N. Woods[182]

(CMS Collaboration)

[1]*Yerevan Physics Institute, Yerevan, Armenia*
[2]*Institut für Hochenergiephysik, Wien, Austria*
[3]*Institute for Nuclear Problems, Minsk, Belarus*
[4]*Universiteit Antwerpen, Antwerpen, Belgium*
[5]*Vrije Universiteit Brussel, Brussel, Belgium*
[6]*Université Libre de Bruxelles, Bruxelles, Belgium*
[7]*Ghent University, Ghent, Belgium*
[8]*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
[9]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[10]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[11a]*Universidade Estadual Paulista, São Paulo, Brazil*
[11b]*Universidade Federal do ABC, São Paulo, Brazil*
[12]*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria*
[13]*University of Sofia, Sofia, Bulgaria*
[14]*Beihang University, Beijing, China*
[15]*Institute of High Energy Physics, Beijing, China*
[16]*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[17]*Tsinghua University, Beijing, China*
[18]*Universidad de Los Andes, Bogota, Colombia*
[19]*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*
[20]*University of Split, Faculty of Science, Split, Croatia*
[21]*Institute Rudjer Boskovic, Zagreb, Croatia*
[22]*University of Cyprus, Nicosia, Cyprus*
[23]*Charles University, Prague, Czech Republic*

[24]Escuela Politecnica Nacional, Quito, Ecuador
[25]Universidad San Francisco de Quito, Quito, Ecuador
[26]Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
[27]National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
[28]Department of Physics, University of Helsinki, Helsinki, Finland
[29]Helsinki Institute of Physics, Helsinki, Finland
[30]Lappeenranta University of Technology, Lappeenranta, Finland
[31]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
[32]Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France
[33]Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
[34]Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
[35]Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
[36]Georgian Technical University, Tbilisi, Georgia
[37]Tbilisi State University, Tbilisi, Georgia
[38]RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
[39]RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[40]RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
[41]Deutsches Elektronen-Synchrotron, Hamburg, Germany
[42]University of Hamburg, Hamburg, Germany
[43]Karlsruher Institut fuer Technologie, Karlsruhe, Germany
[44]Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
[45]National and Kapodistrian University of Athens, Athens, Greece
[46]National Technical University of Athens, Athens, Greece
[47]University of Ioánnina, Ioánnina, Greece
[48]MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
[49]Wigner Research Centre for Physics, Budapest, Hungary
[50]Institute of Nuclear Research ATOMKI, Debrecen, Hungary
[51]Institute of Physics, University of Debrecen, Debrecen, Hungary
[52]Indian Institute of Science (IISc), Bangalore, India
[53]National Institute of Science Education and Research, HBNI, Bhubaneswar, India
[54]Panjab University, Chandigarh, India
[55]University of Delhi, Delhi, India
[56]Saha Institute of Nuclear Physics, HBNI, Kolkata, India
[57]Indian Institute of Technology Madras, Madras, India
[58]Bhabha Atomic Research Centre, Mumbai, India
[59]Tata Institute of Fundamental Research-A, Mumbai, India
[60]Tata Institute of Fundamental Research-B, Mumbai, India
[61]Indian Institute of Science Education and Research (IISER), Pune, India
[62]Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
[63]University College Dublin, Dublin, Ireland
[64a]INFN Sezione di Bari, Bari, Italy
[64b]Università di Bari, Bari, Italy
[64c]Politecnico di Bari, Bari, Italy
[65a]INFN Sezione di Bologna, Bologna, Italy
[65b]Università di Bologna, Bologna, Italy
[66a]INFN Sezione di Catania, Catania, Italy
[66b]Università di Catania, Catania, Italy
[67a]INFN Sezione di Firenze, Firenze, Italy
[67b]Università di Firenze, Firenze, Italy
[68]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[69a]INFN Sezione di Genova, Genova, Italy
[69b]Università di Genova, Genova, Italy
[70a]INFN Sezione di Milano-Bicocca, Milano, Italy
[70b]Università di Milano-Bicocca, Milano, Italy
[71a]INFN Sezione di Napoli, Napoli, Italy
[71b]Università di Napoli 'Federico II', Napoli, Italy
[71c]Università della Basilicata, Potenza, Italy
[71d]Università G. Marconi, Roma, Italy
[72a]INFN Sezione di Padova, Padova, Italy

[72b]Università di Padova, Padova, Italy
[72c]Università di Trento, Trento, Italy
[73a]INFN Sezione di Pavia, Pavia, Italy
[73b]Università di Pavia, Pavia, Italy
[74a]INFN Sezione di Perugia, Perugia, Italy
[74b]Università di Perugia, Perugia, Italy
[75a]INFN Sezione di Pisa, Pisa, Italy
[75b]Università di Pisa, Pisa, Italy
[75c]Scuola Normale Superiore di Pisa, Pisa, Italy
[76a]INFN Sezione di Roma, Rome, Italy
[76b]Sapienza Università di Roma, Rome, Italy
[77a]INFN Sezione di Torino, Torino, Italy
[77b]Università di Torino, Torino, Italy
[77c]Università del Piemonte Orientale, Novara, Italy
[78a]INFN Sezione di Trieste, Trieste, Italy
[78b]Università di Trieste, Trieste, Italy
[79]Kyungpook National University, Daegu, Korea
[80]Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
[81]Hanyang University, Seoul, Korea
[82]Korea University, Seoul, Korea
[83]Sejong University, Seoul, Korea
[84]Seoul National University, Seoul, Korea
[85]University of Seoul, Seoul, Korea
[86]Sungkyunkwan University, Suwon, Korea
[87]Vilnius University, Vilnius, Lithuania
[88]National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
[89]Universidad de Sonora (UNISON), Hermosillo, Mexico
[90]Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
[91]Universidad Iberoamericana, Mexico City, Mexico
[92]Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
[93]Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
[94]University of Auckland, Auckland, New Zealand
[95]University of Canterbury, Christchurch, New Zealand
[96]National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
[97]National Centre for Nuclear Research, Swierk, Poland
[98]Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
[99]Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
[100]Joint Institute for Nuclear Research, Dubna, Russia
[101]Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
[102]Institute for Nuclear Research, Moscow, Russia
[103]Institute for Theoretical and Experimental Physics, Moscow, Russia
[104]Moscow Institute of Physics and Technology, Moscow, Russia
[105]National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
[106]P.N. Lebedev Physical Institute, Moscow, Russia
[107]Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
[108]Novosibirsk State University (NSU), Novosibirsk, Russia
[109]Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia
[110]National Research Tomsk Polytechnic University, Tomsk, Russia
[111]University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
[112]Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
[113]Universidad Autónoma de Madrid, Madrid, Spain
[114]Universidad de Oviedo, Oviedo, Spain
[115]Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
[116]University of Ruhuna, Department of Physics, Matara, Sri Lanka
[117]CERN, European Organization for Nuclear Research, Geneva, Switzerland
[118]Paul Scherrer Institut, Villigen, Switzerland
[119]ETH Zurich—Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
[120]Universität Zürich, Zurich, Switzerland
[121]National Central University, Chung-Li, Taiwan
[122]National Taiwan University (NTU), Taipei, Taiwan

[123]Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
[124]Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
[125]Middle East Technical University, Physics Department, Ankara, Turkey
[126]Bogazici University, Istanbul, Turkey
[127]Istanbul Technical University, Istanbul, Turkey
[128]Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
[129]National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
[130]University of Bristol, Bristol, United Kingdom
[131]Rutherford Appleton Laboratory, Didcot, United Kingdom
[132]Imperial College, London, United Kingdom
[133]Brunel University, Uxbridge, United Kingdom
[134]Baylor University, Waco, Texas, USA
[135]Catholic University of America, Washington, DC, USA
[136]The University of Alabama, Tuscaloosa, Alabama, USA
[137]Boston University, Boston, Massachusetts, USA
[138]Brown University, Providence, Rhode Island, USA
[139]University of California, Davis, Davis, California, USA
[140]University of California, Los Angeles, California, USA
[141]University of California, Riverside, Riverside, California, USA
[142]University of California, San Diego, La Jolla, California, USA
[143]University of California, Santa Barbara—Department of Physics, Santa Barbara, California, USA
[144]California Institute of Technology, Pasadena, California, USA
[145]Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
[146]University of Colorado Boulder, Boulder, Colorado, USA
[147]Cornell University, Ithaca, New York, USA
[148]Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[149]University of Florida, Gainesville, Florida, USA
[150]Florida International University, Miami, Florida, USA
[151]Florida State University, Tallahassee, Florida, USA
[152]Florida Institute of Technology, Melbourne, Florida, USA
[153]University of Illinois at Chicago (UIC), Chicago, Illinois, USA
[154]The University of Iowa, Iowa City, Iowa, USA
[155]Johns Hopkins University, Baltimore, Maryland, USA
[156]The University of Kansas, Lawrence, Kansas, USA
[157]Kansas State University, Manhattan, Kansas, USA
[158]Lawrence Livermore National Laboratory, Livermore, California, USA
[159]University of Maryland, College Park, Maryland, USA
[160]Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
[161]University of Minnesota, Minneapolis, Minnesota, USA
[162]University of Mississippi, Oxford, Mississippi, USA
[163]University of Nebraska-Lincoln, Lincoln, Nebraska, USA
[164]State University of New York at Buffalo, Buffalo, New York, USA
[165]Northeastern University, Boston, Massachusetts, USA
[166]Northwestern University, Evanston, Illinois, USA
[167]University of Notre Dame, Notre Dame, Indiana, USA
[168]The Ohio State University, Columbus, Ohio, USA
[169]Princeton University, Princeton, New Jersey, USA
[170]University of Puerto Rico, Mayaguez, Puerto Rico
[171]Purdue University, West Lafayette, Indiana, USA
[172]Purdue University Northwest, Hammond, Indiana, USA
[173]Rice University, Houston, Texas, USA
[174]University of Rochester, Rochester, New York, USA
[175]Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
[176]University of Tennessee, Knoxville, Tennessee, USA
[177]Texas A&M University, College Station, Texas, USA
[178]Texas Tech University, Lubbock, Texas, USA
[179]Vanderbilt University, Nashville, Tennessee, USA
[180]University of Virginia, Charlottesville, Virginia, USA
[181]Wayne State University, Detroit, Michigan, USA
[182]University of Wisconsin—Madison, Madison, Wisconsin, USA

[a]Deceased.
[b]Also at Vienna University of Technology, Vienna, Austria.
[c]Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.
[d]Also at Universidade Estadual de Campinas, Campinas, Brazil.
[e]Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[f]Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[g]Also at University of Chinese Academy of Sciences, Beijing, China.
[h]Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[i]Also at Joint Institute for Nuclear Research, Dubna, Russia.
[j]Also at British University in Egypt, Cairo, Egypt.
[k]Also at Suez University, Suez, Egypt.
[l]Also at Zewail City of Science and Technology, Zewail, Egypt.
[m]Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia.
[n]Also at Université de Haute Alsace, Mulhouse, France.
[o]Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[p]Also at Tbilisi State University, Tbilisi, Georgia.
[q]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[r]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[s]Also at University of Hamburg, Hamburg, Germany.
[t]Also at Brandenburg University of Technology, Cottbus, Germany.
[u]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[v]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[w]Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
[x]Also at IIT Bhubaneswar, Bhubaneswar, India.
[y]Also at Institute of Physics, Bhubaneswar, India.
[z]Also at Shoolini University, Solan, India.
[aa]Also at University of Visva-Bharati, Santiniketan, India.
[bb]Also at Isfahan University of Technology, Isfahan, Iran.
[cc]Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[dd]Also at Università degli Studi di Siena, Siena, Italy.
[ee]Also at Kyunghee University, Seoul, Korea.
[ff]Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
[gg]Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
[hh]Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
[ii]Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
[jj]Also at Institute for Nuclear Research, Moscow, Russia.
[kk]Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[ll]Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[mm]Also at University of Florida, Gainesville, Florida, USA.
[nn]Also at P.N. Lebedev Physical Institute, Moscow, Russia.
[oo]Also at INFN Sezione di Padova, Università di Padova, Padova, Italy, Università di Trento, Trento, Italy.
[pp]Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
[qq]Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[rr]Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.
[ss]Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[tt]Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[uu]Also at National and Kapodistrian University of Athens, Athens, Greece.
[vv]Also at Riga Technical University, Riga, Latvia.
[ww]Also at Universität Zürich, Zurich, Switzerland.
[xx]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
[yy]Also at Gaziosmanpasa University, Tokat, Turkey.
[zz]Also at Adiyaman University, Adiyaman, Turkey.
[aaa]Also at Istanbul Aydin University, Istanbul, Turkey.
[bbb]Also at Mersin University, Mersin, Turkey.
[ccc]Also at Piri Reis University, Istanbul, Turkey.
[ddd]Also at Ozyegin University, Istanbul, Turkey.
[eee]Also at Izmir Institute of Technology, Izmir, Turkey.
[fff]Also at Marmara University, Istanbul, Turkey.
[ggg]Also at Kafkas University, Kars, Turkey.

[hhh]Also at Istanbul University, Faculty of Science, Istanbul, Turkey.
[iii]Also at Istanbul Bilgi University, Istanbul, Turkey.
[jjj]Also at Hacettepe University, Ankara, Turkey.
[kkk]Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[lll]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[mmm]Also at Monash University, Faculty of Science, Clayton, Australia.
[nnn]Also at Bethel University, St. Paul, Minnesota, USA.
[ooo]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[ppp]Also at Utah Valley University, Orem, Utah, USA.
[qqq]Also at Purdue University, West Lafayette, Indiana, USA.
[rrr]Also at Beykent University, Istanbul, Turkey.
[sss]Also at Bingol University, Bingol, Turkey.
[ttt]Also at Sinop University, Sinop, Turkey.
[uuu]Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[vvv]Also at Texas A&M University at Qatar, Doha, Qatar.
[www]Also at Kyungpook National University, Daegu, Korea.